Calibration and Extension of a Discrete Event Operations Simulation Modeling Multiple Un-Manned Aerial Vehicles Controlled by a Single Operator

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CALIBRATION AND EXTENSION OF A DISCRETE EVENT OPERATIONS SIMULATION MODELING MULTIPLE UN-MANNED AERIAL VEHICLES CONTROLLED BY A SINGLE OPERATOR

THESIS

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Abstract

As Unmanned Aerial Vehicles continue to take a greater role in modern military affairs, the Department of Defense is seeking ways to increase autonomy and to improve interoperability – both within systems of UAVs and between UAVs and the operators that use them. The next step for small UAVs in this direction is for one operator to be able to control multiple UAVs. New tools and capabilities require new tactics, techniques, and procedures to obtain optimal results. There is also a need for a more realistic and versatile simulation that can be used for mission planning to represent the expected results of UAV operations under a wide variety of conditions.

This research improved a simulation that models a single operator responsible for multiple UAV rovers. The improvement calibrated the model by increasing the realism of its expected time that the target will be within the field of view of a UAV's camera and how much of that will be observed by an operator that has multiple tasks to perform throughout the mission.

The calibration was derived from multiple flight tests, by using a Field of View Algorithm in MATLAB and by visually recording times for loiter loops by hand. It was determined that the target will be within the field of view of a UAV loitering in a circular pattern between 62% and 66% of the overall loiter time. For an 8 hour beyond line of sight mission, the model's optimal results were 145 min of Value Added Time in low wind conditions and 137 min in high wind. For an 8 hour within line of sight mission, the optimal mean was 287 min in low wind conditions and 268 min in high wind.

Keep Studying!

(to Mike and Kamilla)

Acknowledgments

This thesis integrated multiple varied tools and fields. It took a great effort on the part of a great many people in order to bring this research and analysis to fruition. First, I would like to thank Dr. John Colombi for his help in identifying potential research ideas and for providing course corrections along the way. Dr. Colombi also spent a considerable amount of time and effort on the manipulation and modification of the MATLAB Field of View Algorithm. I could not have asked for a better thesis advisor.

Dr. Jacques set the AFIT UAV Team up for success by ensuring it received the funding and resources it needed. He also supported the AFIT UAV Team's testing efforts, both in the planning and execution stages.

The flight tests would never have taken place without the tremendous assistance of Don Smith and Rick Patton from Cooperative Engineering Solutions, Inc. Their assistance in modifying, maintaining, and repairing the Un-manned Aerial Vehicles was invaluable. Their experience and expertise were also critical in the execution of flight tests.

Camp Atterbury should be recognized for allowing the AFIT UAV Team to use its runway and airspace for the purpose of flight testing. First Lieutenant Charlie Neal provided critical assistance in transforming telemetry logs into data that could be used in the MATLAB Field of View Algorithm.

It takes a good team to accomplish an epic work like a thesis, but it takes a great team to make it fun!

Jonathan W. Welborn

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I. Introduction

1.1 General Issue

This thesis will seek to optimize tactics, techniques, and procedures (TTPs) for small unmanned aerial vehicles (SUAVs), currently used by the US Army and other agencies. The research will test the validity of a discrete event simulation to determine the optimal TTPs for operating multiple SUAVs cooperatively in order to extend reconnaissance range. One concept to extend range uses one SUAS as a communication “relay” vehicle with another as the ISR “rover”. The scenarios tested in simulation will use one operator to control one to four UAVs. These can be in the form of one to two rover/relay pairs or one to four rovers . Two use case scenarios were selected to mirror potential scenarios for future operators in the field.

1.2 Unmanned Aerial Systems

Unmanned aerial systems have seen extensive operations in counter-insurgency operations in Iraq and Afghanistan over the past decade. The Army, Navy, and Air Force each possess an arsenal of UAVs. The Navy chose to further develop the RQ-4 into the MQ-4C BAMS UAS known as the Triton which the Navy still uses[1]. All three services use the MQ-9 Reaper[2]. The Reaper is an upgraded version of the MQ-1 Predator[2]. The Predator is a mid-range UAV built to conduct reconnaissance at the operational level[3]. The Reaper added the capability to carry a significant payload[2]. It also extended the range and altitude of the Predator and possesses a faster top speed[2].

The focus of this thesis will be small UAVs that are used at the tactical level. The primary SUAV to be considered is a modified version of the widely used, hand portable tactical reconnaissance SUAV known as the RQ-11 Raven. The US Army awarded the SUAV contract to AeroVironment in 2005 to build the Raven and it went into Full-Rate Production in 2006[4]. As of early 2012, AeroVironment distributed over 19,000 airframes to various militaries around the world[4].

The Raven can be flown by remote control or on auto-pilot using GPS waypoints[4]. The Raven can carry one sensor per sortie, either a color video camera or infrared night vision camera[4]. The Raven can stay in the air for 60-90 minutes and has an effective operational radius of approximately 10 km (6.2 miles)[4]. It weighs 4.2 lbs and costs $35,000 for a single Raven or $250,000 for a total system including a ground control station with applicable software and four Ravens[4].

The experimental variant to the Raven that will be used for testing is the AFIT Overhead Watch and Loiter (OWL). The OWL shares the same airframe and propulsion system as the Raven, but the OWL's controls and communications hardware and software are modified.

1.3 Simulations

The simulations used for this thesis are all discrete event simulations using software called Arena which is licensed under Rockwell. The original simulation was created by Capt Wellbaum in his 2010 thesis[5]. This simulation used a series of use case scenarios to show the effects of the number of paired rover/relay teams (between one and four teams) and the time between launching the paired teams on the desired outcome, the time that a rover surveills a target (i.e. loiters over a target) and the time that a user observes the video feedback (i.e. the operator is not performing another task requiring his/her attention)[5]. Capt Wellbaum conducted initial simulation validation by comparing the results of his simulation with the empirical results of test flights run at Camp Atterbury using a single OWL[5]. Due to technical issues with the hardware, no actual rover/relay paired flights were conducted[5].

The second iteration validation was conducted by 1Lt Cottle in his 2011 thesis entitled "Initial Operational Validation of an Unmanned Aerial Vehicle Mission Simulation Model"[6]. Cottle found that the endurance of the UAV in the original simulation overestimates the endurance of the battery by 22% on average and underestimates the occurrence of non-routine maintenance by 14% and the duration of routine maintenance was underestimated by 15%[6]. Cottle applied correction factors to the simulation to more closely resemble the experimental results [6]. The simulation did not cover rover/relay pairs nor three or four simultaneous rover use cases[6].

1.4 Research Objectives

Research objectives were determined by considering the validity of assumptions used by Wellbaum and Cottle in their thesis work for AFIT. It was determined that a fallacy was being introduced into the simulation by a faulty assumption. The entire loiter time over target is being used as the time observing the target, but it is common knowledge among UAV operators that only a percentage of this time is actually captured in observation or recordings. This will be the focus for this thesis.

The research questions will include:

1) What is a more realistic simulation for multiple SUAV operations?
2) How should multiple SUAVs be employed based on an improved simulation?

In order to answer these two questions, the following tasks must be performed:

1) Calibrate and extend the discrete event computer simulation that models operations of one operator controlling multiple UAVs by developing a correction factor to account for the intermittent loss of the target from the field of view of the OWL's camera.

2) Determine optimal Tactics, Techniques, and Procedures for single operators using multiple OWLs to maximize the amount of time that an OWL is observing the target and the operator is watching or is able to watch the video feedback (this will be referred to from now on as Value Added Time).

The completion of these objectives will allow the military to extend the range of its small UAVs beyond line-of-sight and to conduct operations in an optimal manner with confidence using the new TTPs.

1.5 Overview

This thesis follows the standard thesis format. Chapter 1 introduces the research topic, gives background information and definitions, and outlines the rest of the thesis. Chapter 2 discusses relevant literature that contributed to the development of validation techniques pertaining to discrete event simulations. Chapter 3 proposes a methodology for validating the rover/relay discrete event operations simulation. Chapter 4 uses empirical data to draw conclusions based on statistical comparisons to the results of the simulation. Chapter 5 discusses the ramifications of this research and recommendations for future work.

II. Literature Review

2.1 Needs of the DOD

In order to properly engineer a system, the requirements of the primary stakeholders should be considered. This will guide and constrain how to proceed while ensuring research is geared towards the goals of the users. At the highest level, unmanned vehicles and systems are of vital importance because of their persistence, versatility, and reduced risk to human life.

The Office of the Secretary of Defense created a roadmap for integrating unmanned systems for the Department of Defense [7]. The key challenges facing the US military with regard to unmanned systems integration are:

1) Interoperability
2) Autonomy
3) Airspace Integration
4) Communications
5) Training
6) Propulsion and Power
7) Manned-Unmanned Teaming

The first two of these challenges will coincide with the purposes of our simulation and its subsequent calibrations. The Department of Defense goes on to state its vision for unmanned systems which follows:

"…the seamless integration of diverse unmanned capabilities that provide flexible options for the joint warfighter while exploiting the inherent advantages of unmanned technologies, including persistence, size, speed, maneuverability, and reduced risk to human life. DOD envisions unmanned systems seamlessly operating with manned systems while gradually reducing the degree of human control and decision making required for the unmanned portion of the force structure [7]."

The simulation used in this thesis provides a forward look at a type of surveillance that utilizes an increased ratio of unmanned to manned forces and greater autonomy and interoperability in order to achieve greater results envisioned by the Department of Defense.

The purposes of this thesis will especially center on the battlespace awareness. The simulation is seeking out ways to enhance surveillance through cooperative UAV paired teams. Greater confidence in the optimal way to operate these teams will ensure that they are used to their greatest effect.

2.2 Discrete Event Simulation

2.2.1 System Configuration

The system prototype developed by Wellbaum [5] was given the designation of OWL (Overhead Watch and Loiter). This thesis, however, will use the term OWLs to represent the small un-manned aerial vehicles that either conduct aerial reconnaissance (the rover) or act as an airborne communications hub which relays communications from the rover to the ground station (the relay). The operational concept (OV-1 diagram) on the following page is a visual overview of how the system's sub-components work together to complete the reconnaissance mission. In the scenario depicted, a single operator is tasked to observe a convoy of trucks moving out of the direct line-of-sight from the ground station.

In the past, this has been impossible. Using rover/relay paired OWLs, the operator will be able to double the range of SUAS operations. The internal system components necessary to achieve the required observations when operating beyond RF line-of-sight include the ground station, the operator, and at least one rover/relay pair of OWLs.

Any airframe could be used in place of the OWLs as long as it can synchronize transmissions to and from the ground station and possesses enough battery endurance to remain in flight throughout the entire duration of the surveillance. The vehicles are identified in the OV-1 by the roles they are required to perform – either that of a communication relay or an observing rover. The OV-1 also specifies the autopilot used in each UAV. Historically, UAVs used for testing this simulation used Kestrel Autopilot. Due to research being conducted simultaneous with this thesis by Lieutenant Shuck and Captain Songer, the Arduino Autopilot will replace the Kestrel Autopilot. The Arduino costs a fraction of the Kestrel while retaining more adaptability. Lieutenant Shuck and Captain Songer will write the control code onto the Arduino in house, instead of relying on the proprietary technology and programming of the Kestrel. Also represented in the OV-1, are the Virtual Cockpit and video interfaces present on the computer in the ground station and the "Commbox" device which facilitates 2-way communication between the ground component and the air vehicles. Lines of communication are shown, including the necessary interaction with the external Global Positioning Satellite (GPS) system.

The Operational View for the entire small un-manned aerial system is in Figure 1 on the following page:

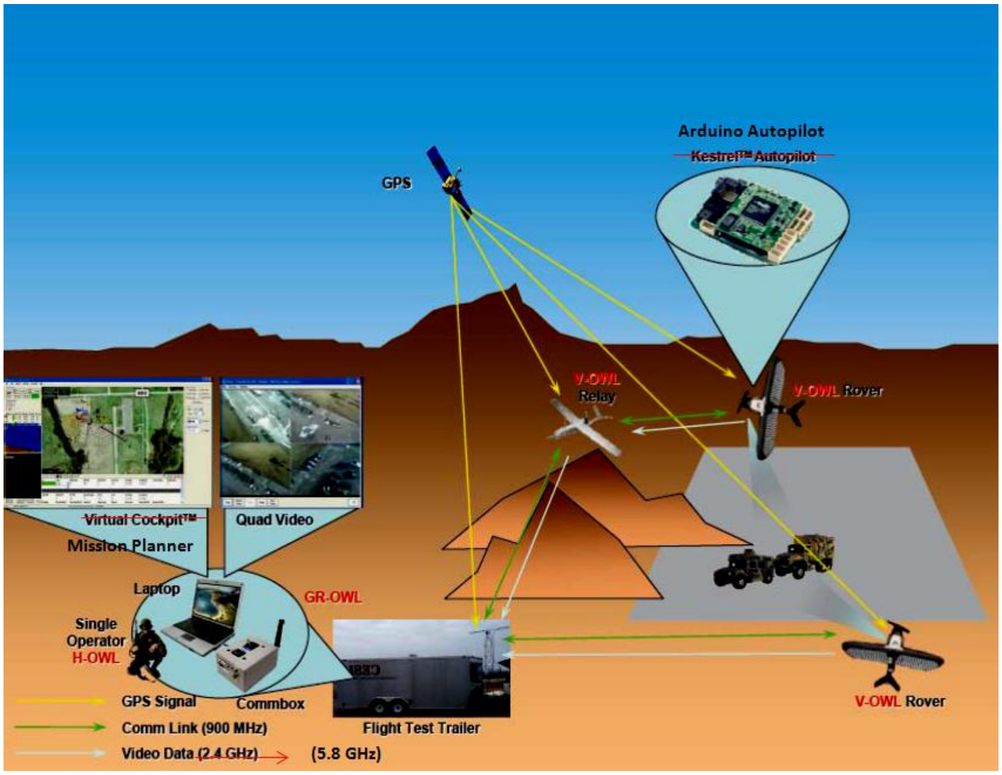


Figure 1: Operational View of OWL system [5]

The airframe that will be utilized for this thesis, the OWL, is based on the U.S. Army's RQ-11A Raven UAV. The original aircraft was acquired and modified to fit AFIT's research purposes with a new power plant and new autopilot and communications system. More details of the modifications and other detailed descriptions of the vehicle can be found in Section 3.2.2 of Seibert, Stryker, Ward, & Wellbaum [5].

2.2.2 The OWL Operation Simulation

The original simulation, created by Capt. Chris Wellbaum in 2010 [5], utilized four use case scenarios:

1) Stationary target within line of sight (LOS) [requiring only a rover]
2) Stationary target beyond line of sight [requiring a rover/relay pair]
3) Obscured stationary target beyond RF range [requiring a rover/relay pair]
4) Moving target missions within and beyond LOS

All UAVs in the operation will be controlled by one operator in the simulation. The purpose of the operations simulation was to determine the optimal tactics, techniques, and procedures to be used in such use cases where a rover will need to have its range extended by pairing it with a relay UAV.

The two measures of performance developed for the purpose of the simulation and consequent validation were Time Over Target (TOT) and Total Value Added Time (TVAT). These were both used as dependent variables in the experiments. Time Over Target describes the amount of time that a UAV was observing a given target. Total Value Added Time consists of the time that a UAV is observing a target, i.e. the time that the UAV is loitering over the target in a surveillance pattern, simultaneously with the operator observing the video feedback, i.e. not being busy maintaining, repairing, launching or retrieving another UAV.

The original simulation used two independent variables per use case scenario. These independent variables that would be input into the simulation to determine effects on the desired outcome are the total number of rover/relay paired UAVs and the Time Between Initial Paired Launch (TBIPL). It was assumed that both rover and relay would be launched together because one relay could communicate with only one rover. This also has a simplifying effect on the simulation because the endurance times for both batteries can be assumed to be the same. The number of rover/relay pairs were varied from one to four by increments of one. The Time Between Initial Paired Launch varied from launching one immediately after the other (0 minutes TBIPL) to waiting 40 minutes between each paired launch with increments of ten minutes. The distance to target in each scenario is varied to understand the effects of distance on the dependent input variables discussed above.

The simulation starts by launching one or more rover/relay teams [or rovers when the target is within line of sight]. The UAVs fly to the target and loiter there until the battery only has enough power left to return to the operator. At this time, the UAV returns to the operator and "Lands". The operator performs necessary preparatory maintenance, called "Turning" in the simulation, represented by a probability distribution. The operator will then determine if there is time to fly another sortie before the end of mission time. If the operator determines that enough time exists, the operator will "Retrieve the UAV" and re-launch the aircraft. Otherwise, the operator will cease operations. All times associated with these actions are based off of probability distributions using means and variances arrived at by numerous tests.

The only time that was not based on a distribution is the time to "Fix an OWL". Due to lack of empirical data on the time it takes to fix an OWL, the simulation designer asked the experts. The experts stated that five minutes was the average time to fix an OWL with a minimum of 3 minutes and a max of 10 minutes. However, these numbers were based off of expert opinion and not empirical data. A triangular distribution was given to this event. Therefore, any time an OWL develops a problem, the simulation will assign a number between 3 and 10 minutes according to a triangular distribution with a mean of five.

This assumption is not an accurate reflection of the variance involved in repair times or in the distribution of repair times. This would be a primary cause of friction between the simulation results and actual results as will be discussed in the next section.

The original simulation accounts for repair time for broken OWLs by assigning each sortie a 1% chance of breaking. This also turned out to be an issue that will be discussed in the next section. Each time an OWL needed repair, it was assigned a hold module which kept the OWL from flying until it was fixed according to the triangular probability distribution listed above.

2.2.3 Initial Validation

Initial Validation was conducted by First Lieutenant Cottle in his 2011 thesis. He conducted flight tests to determine the validity of the 2010 operational model. The empirical evidence suggests that the endurance of the aircraft were over-estimated by 22% in two cases and 100% on the third, that the occurrence of non-routine maintenance was under-estimated by about 14%, and that the duration of routine maintenance was over-estimated by 15% [6].

Cottle hypothesized that the over-estimation of battery endurance was caused by the fact that Wellbaum's simulation allowed the aircraft to fly until the batteries were completely exhausted. When conducting operations, however, the operator never allows the aircraft to fly until the battery is completely exhausted because the measurement of the voltage is not precise. This would pose a considerable risk of losing the aircraft or damaging the batteries. Therefore, operators adopt a cushion when flying the OWLs to ensure that the battery voltage does not go below a reasonable level before returning the OWL to the operator. Also, strong wind gusts have negative effects on the battery endurance. This was not accounted for in the original simulation.

Cottle also states that the non-routine maintenance actions recorded did not fit neatly into the triangular distribution for the Repair process. This casts doubt on the validity of this probability distribution.

After determining gaps between the simulation results and experimental results, Cottle created correction factors and applied them to the simulation's probability distributions to achieve more accurate simulation results.

2.3 Verification and Validation of Discrete Event Simulations

Verification is defined by Banks, Carson II, Nelson, & Nicol [8] as "…assur[ing] that the conceptual model is reflected accurately in the operational model." The purpose of model verification, in other words, is to ensure that the model is functioning properly according to its design.

Validation is "…the *overall process* of comparing the model and its behavior to the real system and its behavior" [8] . So, validation seeks to ensure that the model inputs the relevant parameters and result in the same output that you would expect from the actual system. A hard look must be taken at the assumptions necessary for the simulation and their effects on the outcome of the simulation. Validation often uses statistical analysis to determine how accurately the behavior of the model should reflect that of the system.

When it comes to validation, there are four areas that must be checked. A proper validation must check the validity of the input data, the transformative model, the output data, and the assumptions. It is helpful to identify the required amount of accuracy for each validation [9].

Before starting validation, a framework should be established. Naylor and Finger [10] put forth a three step process for validating models that will serve as a foundation for this calibration:

"Step 1. Build a model that has high face validity.

Step 2. Validate the assumptions.

Step 3. Compare the model input-output transformations to corresponding input-output transformations for the real system."

This thesis is a prime example of a calibration. The term "calibration" refers to the iterative process of validation. Each time a modeler compares the simulation to the real system, adjustments are made. Each time adjustments are made, the modeler must compare the revised simulation to the system being modeled[8]. This validation will be the third iteration in the calibration sequence.

Validation of assumptions should actually be conducted as soon as the face validity is confirmed. The assumptions must match the system operation to a high degree of fidelity. Variables can be assumed out of the simulation only if they do not affect the outcome of the system [8]. Assumptions can be useful tools to simplify simulations, but if a different outcome is possible from an assumption proving false, the decision maker should receive this information before making the decision.

For this specific calibration of the simulation model, data collection will be of vital importance. Before the simulation can be validated, the data should be validated [11]. Data validation is often not conducted because it is "difficult, time consuming, and costly to obtain sufficient, accurate, and appropriate data" [12]. Two issues in data validation that should be considered are [11]:

1) How should the trial be designed?
2) What data should be collected?

Often during data collection, it is impossible to obtain a large enough sampling to provide statistical validity [11]. This can be problematic and could potentially pose a problem for the OWL operation simulation as there is limited time to conduct flights. Cowdale recommends Design of Experiments methodology to plan data collection techniques [11].

When it comes to data collection, Cowdale makes 6 recommendations to be successful [11]:

1) "Think very hard about what you want.
2) If in doubt collect it.
3) Make sure you are collecting what you think you are collecting.
4) Ensure you document what you collected and what you didn't
5) If possible confirm via two sources.
6) Remain Flexible."

These tips will be useful when designing and executing future experiments.

Checking the face validity is the first step in validating the transformative model. Face validity is the reasonableness of the simulation when compared to the system by experts. Sensitivity analyses are often used to check the model's face validity [13].

The final validation is output analysis. Balci recommends using design of experiments and statistical inference for output analysis [13]. Techniques of output analysis follow [8], [14]:

1. ***Response-surface methodologies*** *can be used to find the optimal combination of parameter values which maximize or minimize the value of a response variable.*

2. ***Factorial designs*** *can be employed to determine the effect of various input variables on an output variable.*
3. ***Variance reduction techniques*** *can be employed to determine the effect of various input variables on an output variable.*
4. ***Ranking and selection techniques*** *can be implemented to obtain greater statistical accuracy for the same amount of simulation.*
5. ***Method of replication, method of batch means, regenerative method****, and others can be used for statistical analysis of simulation output data.*

2.4 Current Status

Cottle [6] referred to a diagram from Sargent's work [15] describing the process of model construction. For continuity and to show further progress in the iterative calibration cycle, this illustration is shown in Figure 2 below.

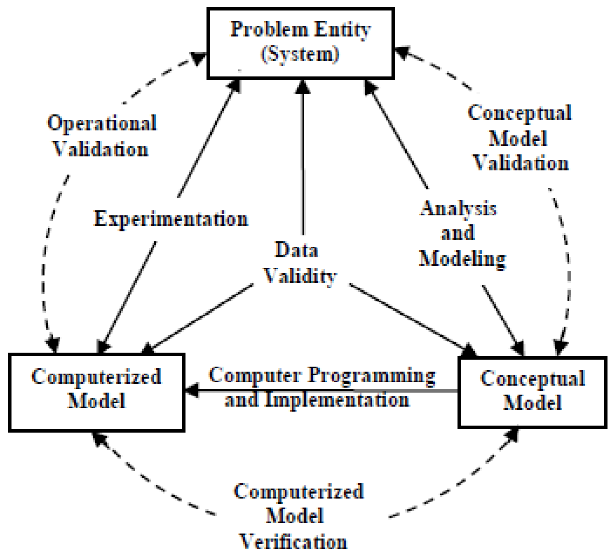


Figure 2: Simple depiction of the modeling process (Sargent, 2009)

Wellbaum [5] established the system, created the conceptual model, and used Arena discrete event simulation software to write the computerized model. Wellbaum went on to conduct verification of his simulation. Cottle [6] conducted test flights to validate the model. He then incorporated his findings back into the conceptual model and computerized model using correction factors. Thus, the modeling process has come full circle and is ready for the next iteration of validation.

2.5 Conclusion

The literary review covered the current body of knowledge on validation of discrete event simulations, the past iterations of simulation validation, and introduced the current status. Also, the original simulation was explained for background purposes. The next chapter will explain the design of the experiments used to further calibrate the original simulation.

III. Methodology

3.1 Conceptual Model Validation

The conceptual model must be considered in an attempt to validate the simulation. First, the validation must ensure that the intent of the simulation correlates with DoD goals. Then, the operational concept of the simulation must be compared to the actual operation of the Raven to ensure that flaws are not being introduced into the simulation from faulty operational assumptions. After confirming the above correlations and assumptions, the model will possess a basic degree of fidelity in the big picture.

The first step in this validation is to ensure there is value in our use case scenarios and our ability to simulate them. Our use case scenarios involve one to four rovers or rover/relay pairs conducting surveillance on various targets and being operated by a single operator. This experiment will focus on two use cases. The first use case will be a single stationary target within line of sight. The second use case will be surveillance of a road, where the road will be simulated by a runway.

The Chairman of the Joint Chiefs of Staff listed in its Universal Joint Task List as a critical task for each service the surveillance of targets and environments [16]. Surveillance serves as a foundation for this simulation. Using paired rover / relay teams, the UAVs cooperate to increase their effectiveness. This correlates well with the guidance from the Secretary of Defense to increase interoperability. Meanwhile, the enhanced surveillance capabilities fulfill the critical task of surveilling targets and environments listed by the Joint Chiefs of Staff.

The Joint Capability Areas (JCAs) were created by the Department of Defense to provide a framework for comparing capabilities and capability gaps across services. The

Joint Capability Areas for unmanned systems are battlespace awareness, force application, protection, and logistics [7].

It appears that the goals of the thesis are closely aligned with those of the Department of Defense and the Joint Chiefs of Staff. Therefore, to complete conceptual validation, all that remains is to see if the simulation actually models what the operators will experience.

It is not impractical to believe that operators would use OWLs in a manner similar to current use of Ravens. Currently, operators fly one Raven as a rover at a time to observe a given target. Users are not currently flying multiple rovers simultaneously or using paired rover/relay teams. If, however, this thesis validates the results of prior OWL operation simulations and funding is available, the military could adopt these Tactics, Techniques, and Procedures.

Some assumptions must be made to conduct experiments for the OWL operations simulation that might differ from actual operations. The test environment is an extremely controlled environment that will be discussed below. In operations, there are many more variables that will surely develop that are not considered in flight tests. Most of these pertain to the difficulties of operating in a hostile environment.

The flight tests are conducted without interference. For example, in an operational environment the repair rate used in the simulation would be much higher and the times longer because of hostile fire. Also, the time to recover a downed or broken UAV could be much longer. The UAV may not be recoverable at all. These are serious differences that the simulation does not address. Obstacles and/or enemy fire can wreak havoc on distributions established for simulation times.

Another assumption that is questionable is that the camera is focused on the target 100% of the time that the UAV is loitering. The camera on the OWL, as well as the Raven, is fixed and can temporarily lose sight of the target while turning, flying in windy conditions or from flight patterns not matching ideal patterns. Thus, further testing and analysis is needed to find the true percentage of time that the target is in the field of view of the camera while loitering.

This Time Loitering over Target to Time Observing Target ratio can be used to create a correction factor and apply it to the original simulation. This correction factor along with the factors created by Cottle should make the simulation more accurate to the real world and more valid for any potential users.

Other assumptions hold true. The effects of strong wind gusts and user judgment are accounted for using Cottle's correction factors that were applied to the UAV simulation. Since the combat effects cannot be simulated easily in a testing environment, they must be assumed to be negligible for purposes of the simulation and testing.

3.2 Experimental Approach

3.2.1 Testing Environment

Testing will be conducted in the form of flight tests at a designated runway at Camp Atterbury that has been of historical use to prior AFIT UAV teams. The range is run by military personnel stationed at Camp Atterbury. Flight planning and operation is assisted by Cooperative Engineering Solutions, Inc. (CESI). CESI consists of a small group of contractors stationed at AFIT's Advanced Navigation Technology (ANT) Center. Experiments are designed and conducted by AFIT UAV team members.

One constraint when using the runway consists of having to share it with helicopters on the adjacent helipad or other low flying aircraft. Clearance must always be obtained from the tower before flying any aircraft, including the AFIT UAV Team's unmanned aerial vehicles.

Another environmental concern is that of weather. Strong winds, rain or lightning can cause the flight tests to shut down. Even mild winds of 15 knots or less have been shown to reduce battery life, thus throwing off the test results. To combat against potential weather hazards, the AFIT UAV Team generally requests one more day than is needed for experimentation in order to shut down operations on a day of bad weather and still be able to gather all necessary test data by using the backup day to fly.

The AFIT OWLs are maintained and modified by the AFIT UAV Team with Cooperative Egineering Solutions, Inc. (CESI) providing consulting, equipment support, and flight support. During operation of the OWL at Camp Atterbury, there must always be a certified pilot to fly the OWL manually in case of communication failure between the OWL and the comm box. It also protects the team from losing an OWL due to GPS failure or a failed autopilot. Finally, funding constrains the experiments that can be conducted and the amount of data that can be collected, and tech support provided.

3.2.2 Test Setup

To record data, the OWL will send telemetry to the ground control station at a rate of 10 times each second. This will be recorded for future analysis. Also, a video transmitter operating on a wavelength of 5.8 MHz will be integrated into the OWL to send video feedback to the ground station. The video will be observed on the screen as well as recorded to DVDs for future reference.

3.2.3 Experimental Design

The Measure of Effectiveness used by both Wellbaum's simulation and Cottle's initial validation was the Time that the OWL Observes the Target. However, the Time Observing Target event in the simulation is assumed to be the entire time that the OWL maintains a loiter pattern over an assigned target. The assumption is that 100% of the time that the OWL is loitering over the target, the target is in the field of view of the camera. This assumption is suspect and further verification is needed.

Also, the AFIT UAV Team has altered many hardware components to improve performance and flexibility while reducing cost. The team replaced the Kestrel Autopilot with the Arduino Autopilot which costs less and allows the UAV Team to add its own code. This brings into question the input data distributions developed by Wellbaum and the correction factors used by Cottle.

For these purposes, the AFIT Team will execute a series of test flights to train and familiarize the team members, evaluate the equipment, and to gather information for simulation validation purposes.

First, the AFIT UAV Team will fly a series of familiarization flights over the course of two days. The goal for these flights is to certify team members on UAV operations conducted at Camp Atterbury. The team will familiarize itself with range safety, UAV operations, flight software, and UAV maintenance. The OWL will be the primary vehicle for these flights. The UAV Team will fly two OWLs on autopilot simultaneously to ensure equipment and user operations are functional.

The second flight test series will take place at Camp Atterbury over two days. The flight test will verify the new autopilot and the inter-communications between OWLs. There will be no operational data gathered at this flight test.

The third flight test series will take place at Camp Atterbury over the course of three days. There are multiple test objectives for this flight test. Six test objectives will be to further verify the functionality of the hardware. These are necessary, but not necessarily relevant to the efforts of this thesis. The seventh test objective will further the purposes of this thesis.

The seventh test objective is to determine the ratio of time that an OWL keeps a target in its field of view to the amount of time that the OWL loiters around the target. This will potentially give a correction factor to apply to Wellbaum's operation simulation.

For the purpose of accomplishing this test objective, the UAV Team will fly the OWL in an operational manner for no less than 30 minutes using two use cases. The first use case will have a single OWL monitoring a stationary target within communications line of sight. The OWL will fly directly to the target and will then loiter over the target. The second use case will use the OWL to conduct surveillance on a roadway (simulated in our experiment by a runway on the flying range plus adjacent roads). For this use case, the OWL will fly an elongated racetrack pattern over the zone of observation.

While the OWL is flying its route and surveilling the target, it will also send video feedback to the ground control station. There the feedback will be monitored on a screen and recorded using a Digital Video Recorder (DVR). The data will be written onto a DVD-R. This will allow analysis to determine the ratio in question.

Independent variables that will be noted for this test are wind speed, camera type, speed of the OWL, and operating height. The camera type is side facing infrared. The wind speed will depend on conditions. The OWL will fly at a speed of 30 mph and an elevation of 300 feet. Further variation can be used with speed and elevation, if time and weather permit, for a more in-depth analysis upon completion of the tests.

While one team member runs the ground control station and records telemetry data, a second team member will observe and record data video feedback from the operation.

3.3 Summary

The data gathered from the above experiments will be applied to the original simulation and Cottle's additional correction factors to enable the simulation to be applied to the new software and hardware configuration with confidence. It will also be used to create a new correction factor that will be applied to the primary measure of effectiveness for the operational simulation – the Time the Target is Observed and the Total Value Added.

IV. Results and Analysis

4.1 Operational Test Flight Results

The flight testing took place over a three day period from 5-7 November 2012. Multiple sorties were flown. Winds throughout the test period were low, between 0-5 mph with gusts up to 10 mph. The temperature ranged from 25 – 50 degrees Fahrenheit.

A hardware problem burned out the cameras in the nose cones of the OWLs by the end of the first day. However, telemetry was recorded from three operational test flights and video was recorded from a fourth. These data points will serve as input data that will be analyzed and transformed into a distribution that can be used in the simulation.

The flight tests were designed to resemble tactical surveillance missions. The two scenarios used were the overhead circular loiter and the overhead racetrack pattern. The circular overhead loiter pattern was re-created, using actual telemetry from a test flight, via a MATLAB algorithm to estimate camera aimpoint and zero elevation footprint. This will be discussed in greater detail in Section 4.2. Figures 3-9 were all created using the aforementioned MATLAB algorithm. Figure 3, on the following page, used the MATLAB algorithm to plot the flight path of an OWL in a circular loiter pattern:

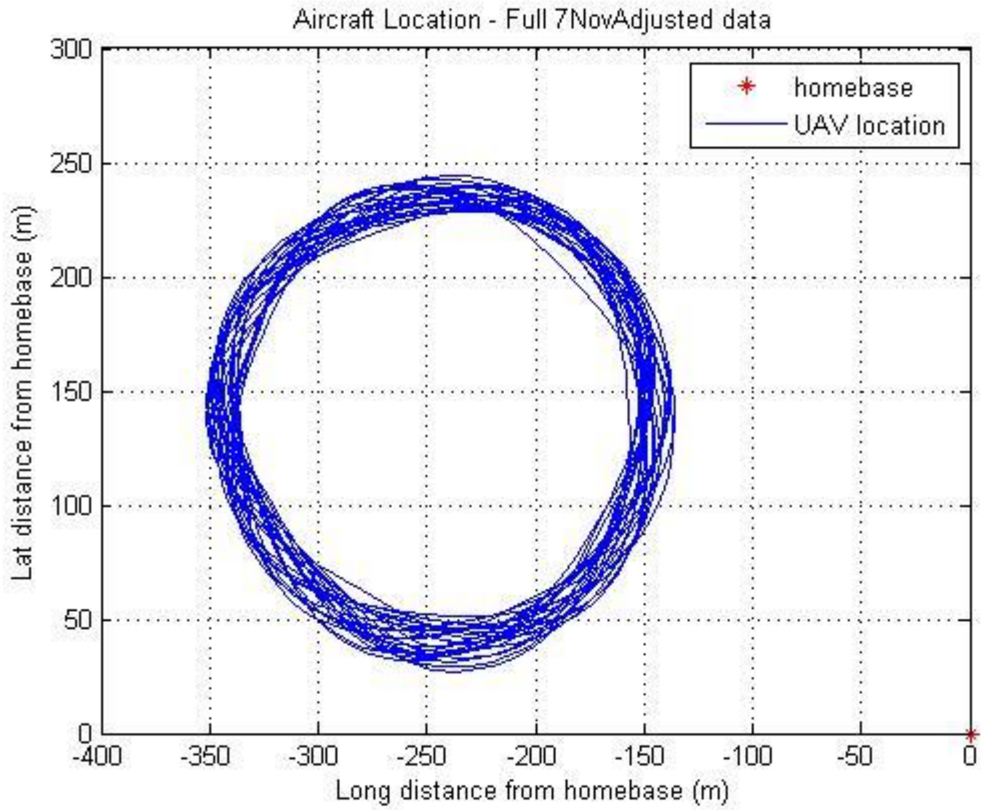


Figure 3: Flight pattern of an OWL in a circular loiter

The same program was used to re-create the flight of a racetrack pattern loiter that was used to monitor a runway (used to represent monitoring a road). It can be seen in the pattern the effects that even a light wind can have on the loiter pattern. The racetrack loiter pattern can be seen in Figure 4:

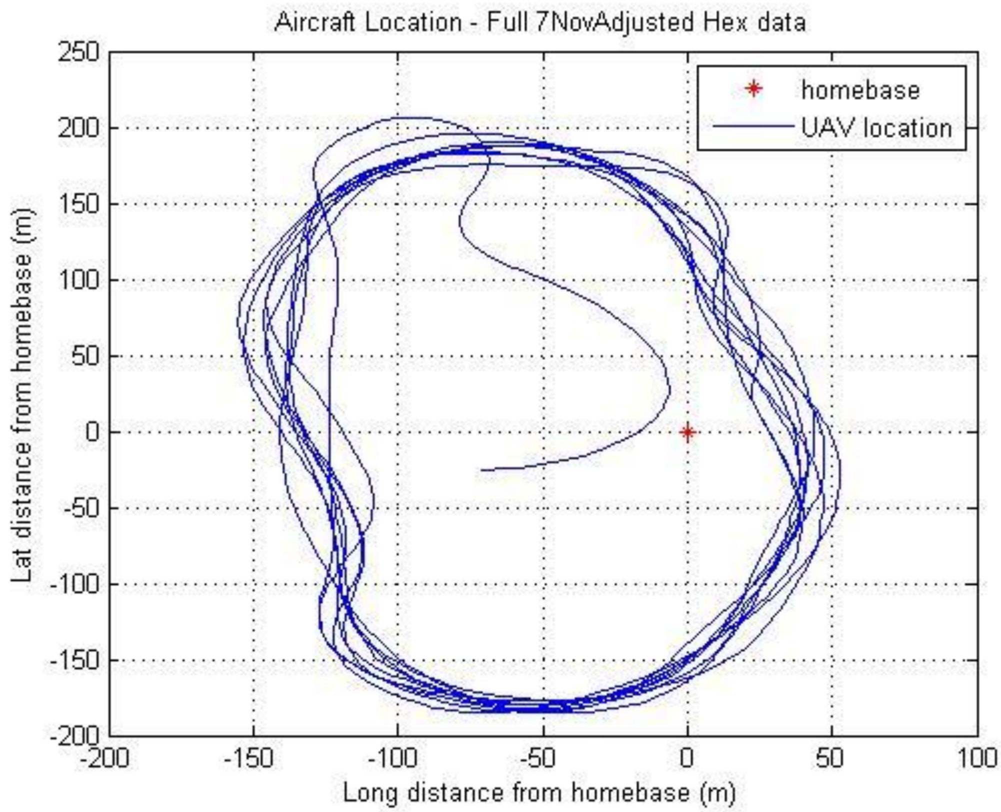


Figure 4: Flight pattern of an OWL in a racetrack loiter

The curve in the middle of the pattern was part of its launch and approach to the pattern. These data points were not considered when determining the percentage of the time that the OWL was observing the target.

The circular loiter pattern represent the surveillance of a stationary target. The racetrack pattern represents the surveillance of a road. Video feedback was only gathered on the racetrack pattern loiter. This data was recorded and measured to provide the following results where each observation represents one complete lap and the percentage of time that the runway could be seen:

Table 1: Percentage of Target Observed Time vs. Loiter Time (manual assessment)

Racetrack Pattern	Lap 1	65%
Racetrack Pattern	Lap 2	60%
Racetrack Pattern	Lap 3	57%
Racetrack Pattern	Lap 4	68%
Racetrack Pattern	Lap 5	66%
Racetrack Pattern	Lap 6	60%

The amount of time the camera is focused on the target should closely resemble that of the tactical scenarios. One constraint that might alter the results is that, during the test for the roadway surveillance scenario, the target was limited to the length of the runway. With a longer target, such as a roadway, the turn time would be less. This would cause tactical missions to have a higher ratio of time that the target is observed compared to total loiter time. Also, the calm winds will result in a higher ratio of the same statistic for tests as opposed to expected results for flights on windy days.

On the third day of flight testing, another surveillance mission was flown utilizing both scenarios but without any video feedback. This was to increase the sample size from which telemetry data for the tactical mission set will be drawn.

4.2 Field of View Algorithms

In order to determine a more precise method of measuring target observed time versus loiter time (and to be able to use telemetry data from flight tests), an algorithm written in MATLAB was used. This algorithm originally came from Lozano's thesis work in 2011[17]. It was slightly modified to better comply with our sorties (both clockwise and counterclockwise loiters).

The Sensor Aimpoint function takes location, attitude and camera selection. Location of the UAV is expressed in meters (latitude, longitude and elevation) in relation to the start point or base, in a North (positive x axis), West (positive y axis) frame. Attitude reflects the yaw, pitch, and roll in an aircraft reference frame. Positive yaw is counter-clockwise, positive pitch is nose up and positive roll is counterclockwise (right wing up). The camera assumes a RAVEN RQ-11 body which has a nose with two cameras out the front and left side (90 degree yaw from nose). The left camera is depressed toward the ground 39 degrees. The front sensor is depressed toward the ground by 49 degrees. While the RAVEN RQ-11 body does not have a right side camera, we assume one could be present with the same 49 degree downward look angle as the left.

The Sensor Footprint function also written in MATLAB takes location, attitude and camera selection. However, this MATLAB function also makes use of the camera field of view (FOV) to project a footprint (trapezoid) on the 0 elevation plane. From earlier work by Lozano, this function assumes an approximate FOV of 48 degrees horizontal and 40 degrees vertical, or ± 24 degrees and ± 20 degrees respectively.

Data is saved and processed every tenth of a second from the raw telemetry. For stationary loiter points, one can check if a hypothesized target (located at the loiter point) is contained within the sensor footprint. Then a percentage of data points that contain the target with respect to all data point can be calculated. Two flight test scenarios, which contain dozens of rotations around a loiter point, contained 7000 and 14,000 samples. It should be noted changes in elevation have a distinct impact on all other aspects of the simulation. The circular loiter pattern with aim points, derived using the above functions and plotted on a two-dimensional graph, looks as follows:

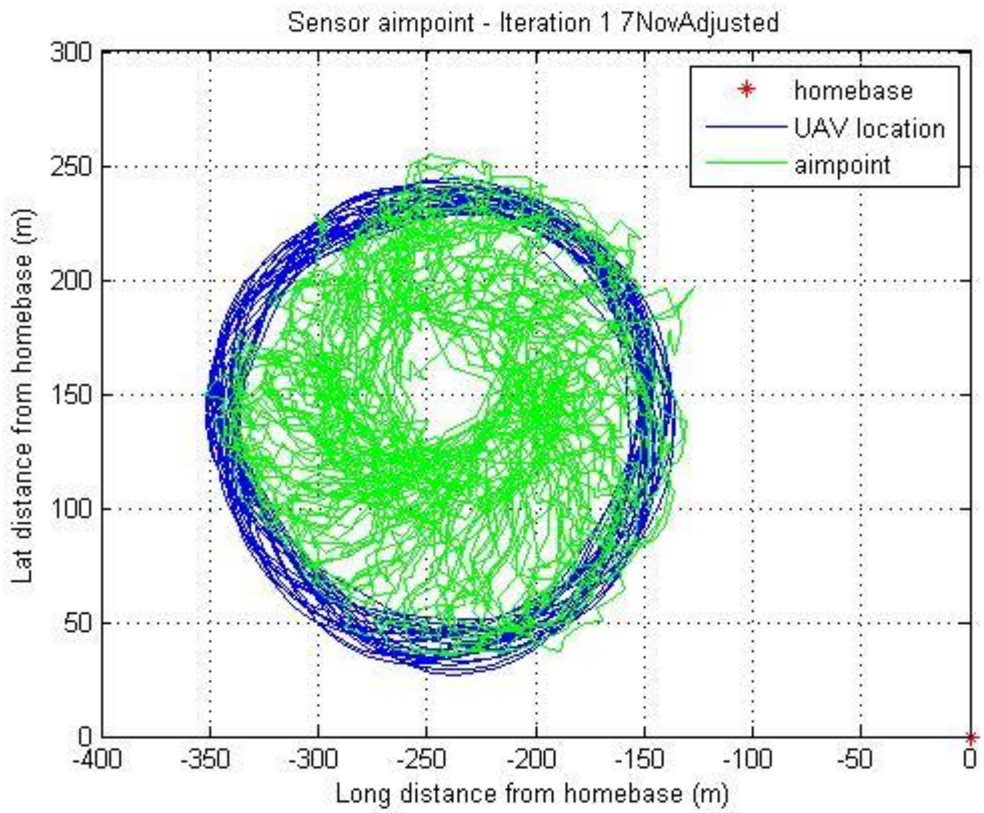


Figure 5: Flight pattern of an OWL in a circular loiter pattern with aimpoints included

The above simulation included every aimpoint. This is useful for seeing the densities of the locations of the aimpoints. The densest section forms a circle directly around the target. A smaller radius loiter would have tightened the aimpoint density into a solid point in the middle of the loiter rather than the empty space as seen above.

Next, the footprints will be added. If every footprint were included, it would be difficult to see patterns. Therefore, one lap is observed with footprints. This can be seen in Figure 6:

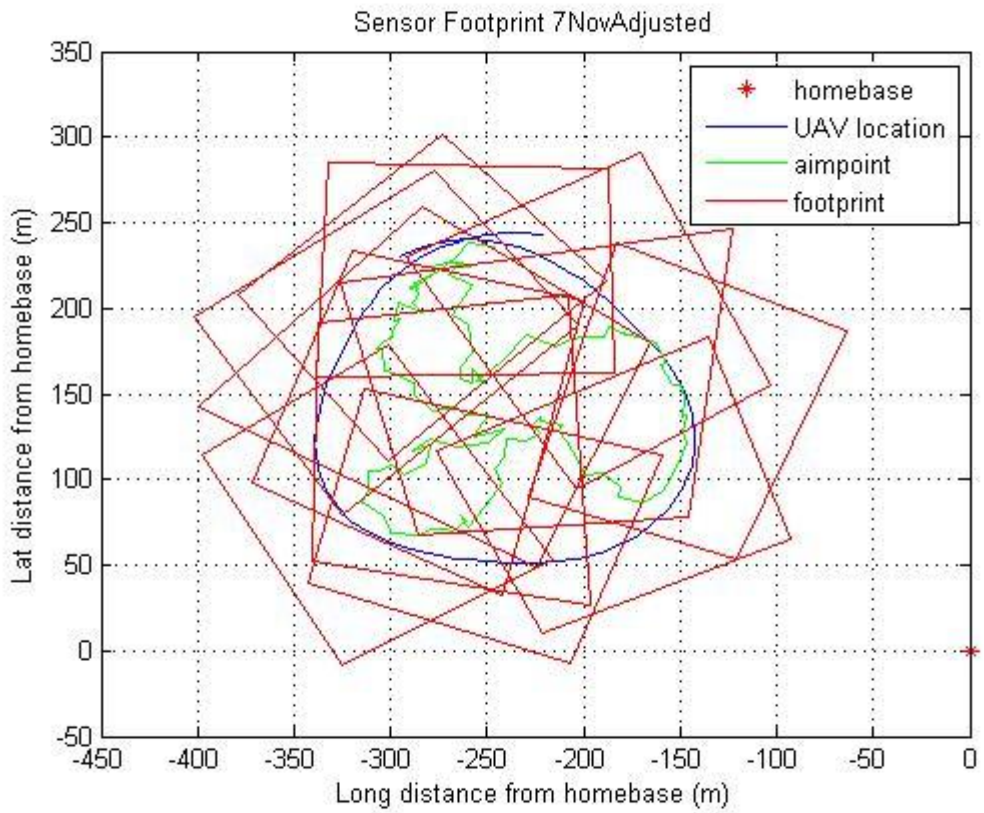


Figure 6: Flight pattern of an OWL in a circular loiter pattern with aimpoints and footprints for one lap

The effects of the wind can be seen in the erratic behavior of the green aimpoint trace. This is a constant effect that causes the UAV to roll back and forth at a rate and range that depend on the wind speed and rate of change. These flight tests were conducted in low winds. However, the effects of these winds are still noticeable.

To better see the effects of flight on the aimpoint and footprint, a smaller section of the loiter pattern has been isolated and more points are shown over this small period. This figure can be seen below:

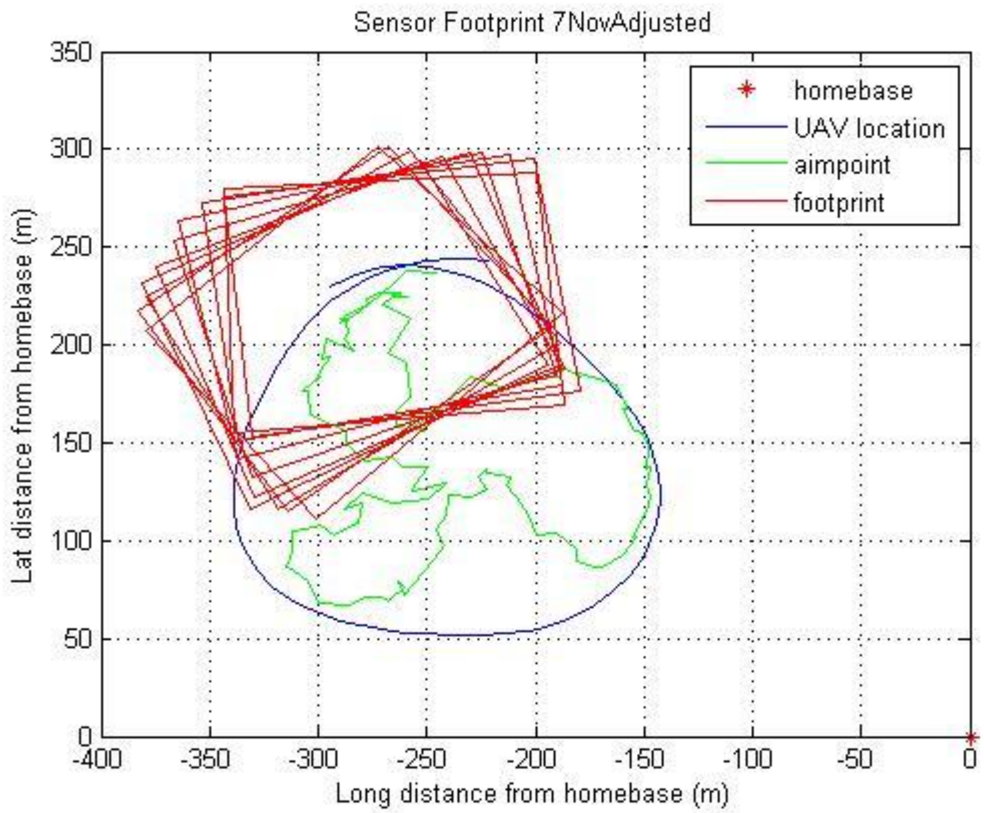


Figure 7: Flight pattern of an OWL in a circular loiter pattern with aimpoints for a lap and footprints for a small period of flight

In the above figure, it can be seen how, although the footprint constantly changes, there is a heavy concentration at the middle of the pattern. This is very close to where the target would be located.

The racetrack loiter pattern has quite a bit more variance in its flight, due to the pattern. The figure below represents the racetrack loiter pattern achieved during the flight tests conducted earlier with the location of the aimpoints on the same two-dimensional map as was shown for the circular loiter pattern. All aimpoints for the entire mission were included again to better see the densities. Racetrack loiter pattern with aimpoint densities is shown below:

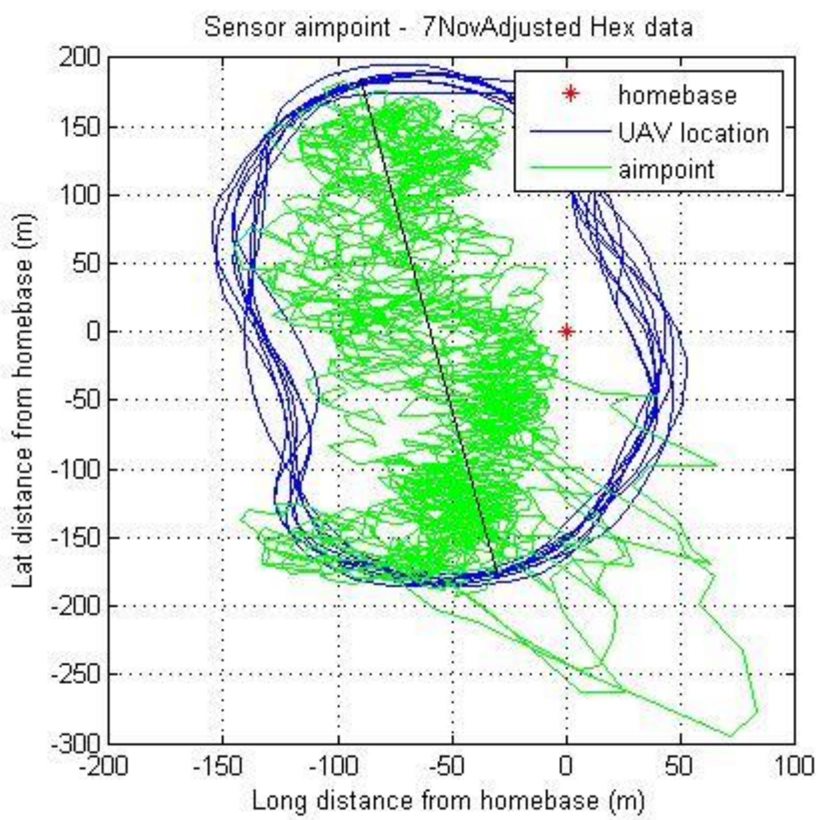


Figure 8: Flight pattern of an OWL in a racetrack loiter pattern with aimpoint densities

The above figure shows the effects of slight winds via the wavy motion of the aimpoints inside the loiter pattern. The effects of sudden wind gusts can be seen during the times where the aimpoint has left the loiter pattern entirely (evidently due to high roll). The highest densities of aimpoints follow very closely to the linear target, i.e. the runway representing a road.

When a few footprints are included in the simulation outputs you get the following:

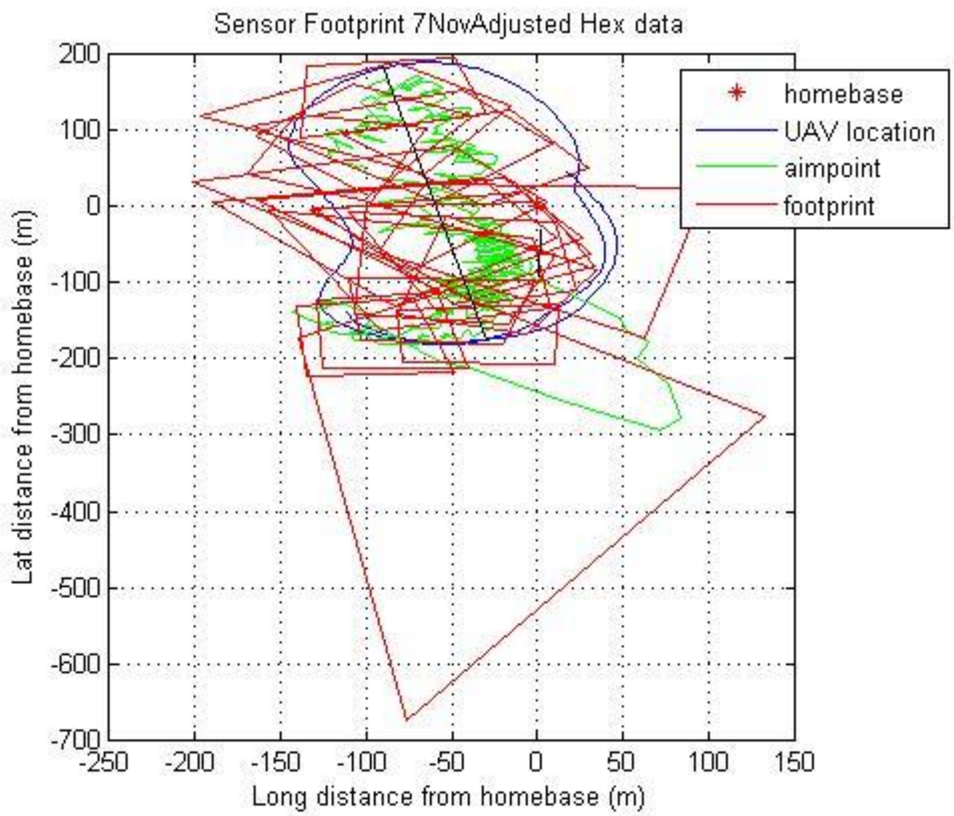


Figure 9: Flight pattern of an OWL in a racetrack loiter pattern with a few aimpoints and footprints

The variance in the placement and size of the footprints is easy to see. The smaller the footprint the more the UAV was aimed straight down. The larger footprints were caused by strong gusts of wind that caused the UAV to roll substantially. With the exception of a few outliers, the vast majority of footprints fell around the linear target.

The above figures help understand the capabilities of the UAV and its limitations. The flight patterns and aiming of the camera are fairly reliable but are definitely not perfect. This is why there needs to be a correction factor for the amount of time that the UAV is loitering over the target compared to the amount of time the UAV is actually observing the target.

The modified Field of View Algorithm also gathered the percentage of time that the target location fell inside the footprint for the circular loiter pattern. Telemetry data for two circular loiter pattern sorties were run through the simulation. The first had 14,000 data points and resulted in a target observed time percentage of 62%. The second simulation used 7,000 data points and resulted in a target observed time percentage of 66%.

These readings correlate very closely with the experimental flight video recording measurements discussed earlier in this chapter that resulted in a mean target observed time percentage of 63% and the distribution derived from input analyzer of .55 + .15 * BETA (1.06, 1.02) that was used in the simulation to represent the target observed time percentage (the derivation of this distribution is discussed in greater detail in Section 4.3.1 and can be seen in Figure 10). The results of the Field of View Algorithm further strengthen the validity of the data and assumptions used for our correction factors.

4.3 Operations Discrete Event Simulation Results

The percentage of time that the OWL rover is observing the target in comparison to the time that the OWL rover is loitering over the target (determined in sections 4.1 and 4.2) can be input into the previous two simulations as a correction factor and the results can be compared.

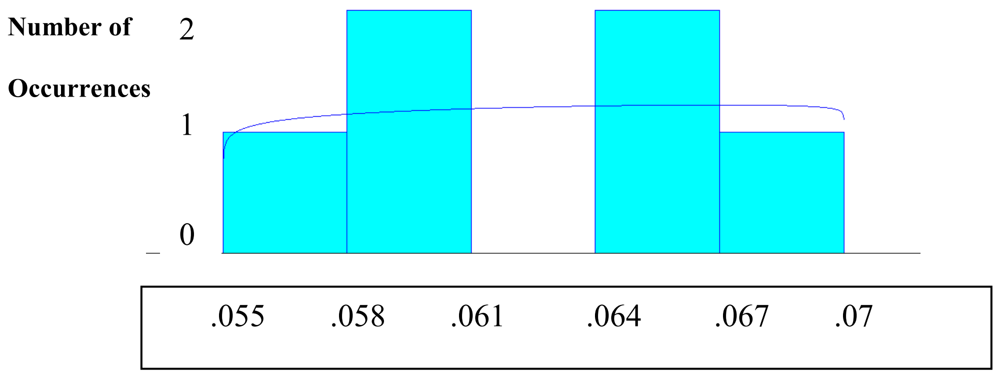
For each simulation, a method called Common Random Numbers will be used to obtain results that have less variance induced by the simulation. Random numbers used in the computer simulation are not truly random. Computer programs are incapable of creating a truly random number.

The simulation can, however, create a series of numbers that closely resemble random numbers. By repeating the same streams of random numbers created by the simulation, the simulation inputs the same random numbers into each varying run. This allows the user to better focus on the variance of the operational data without introducing variance into the system created by the random number generator.

4.3.1 Development of the Time Observing Target Correction Factor

The experimental data obtained from the flight tests must be transformed into a correction factor that can be applied to the simulation in order to change its behavior to more accurately reflect that of reality without changing the behavior of the other processes already modeled.

First, the input data must be analyzed. To do this, a tool within the Rockwell Arena software can be utilized called Input Analyzer. This tool aids in ascertaining the best fit probability distribution to match the experimental data. The results from this analysis are shown in Figure 10 on the following page:



Percentage of Target Observed Time vs. Loiter Time

Distribution Summary		Data Summary	
Distribution:	Beta	Number of Data Points	6
Expression:	0.55 + 0.15 * BETA(1.06, 1.02)	Min Data Value	0.57
Square Error:	0.077647	Max Data Value	0.68
		Sample Mean	0.627
		Sample Std Dev	0.0427
Kolmogorov-Smirnov Test			
Test Statistic	0.152	Histogram Summary	
Corresponding p-value	> 0.15		
		Histogram Range	= 0.55 to 0.7
		Number of Intervals	5

Figure 10: OWL Rover percent of Time Over Target that the UAV Observes the Target Histogram, Fit with Probability Distribution

The Best Fit was applied by the Input Analyzer tool in the Arena simulation software. The Best Fit command compares the p-values and square errors from each distribution fit to the input data to determine the distribution that most closely resembles the data. The results of this data input analysis showed that the Beta distribution most closely resembles the input data. More data points from test flights would have strengthened the conclusion that the Beta distribution is the best fit for future simulations.

Using the distribution arrived at from the Input Data Analysis Best Fit command, the expression that best represents the experimental data, the Time Over Target Correction Factor is derived. It will be applied when a single UAV is loitering over the target. The Time Over Target Correction Factor that will be integrated into the modified discrete event operations simulation is shown below:

corrected_time_over_target =

(0.55 + 0.15 * BETA(1.06, 1.02)) * time_over_target

Note: where BETA represents the Beta distribution

4.3.2 Integration of the TOT Correction Factor into the Simulation

The simplest solution would be to simply multiply the un-modified Time over Target by the average ratio received from experimentation. However, this will not be an accurate reflection in the simulation. It does not account for the possible variation in the ratio of time that the target is observed to time that the UAV loiters over the target.

Another way to model this would simply be to create a distribution based off of experimental results and apply it to reduce the Time Over Target module. This would properly reduce the amount of time that the UAV is observing the target and would introduce the correct amount of variance by using the distribution. However, it still does not accurately represent the effects of the broken continuum of the OWL observing the target.

When the OWL loiters over the target, the loiter time will be represented by, for the purposes of the simulation, the same distribution of time. If the above method were used, the time observing the target would be diminished but without breaks. What the simulation needs is a way to represent one to four OWLs loitering over the target and the field of view of the OWLs being intermittently broken at random times that are independent of one another.

In a one rover simulation, the above method will continue to offer the correct solution. However, once multiple rovers have over lapping loiters over a single target, a more sophisticated means of recording Value Added Time and Target Observed Time is needed.

In order to assign probabilities of total failure to each set of UAVs loitering over the target, the time that there are 1, 2, 3, or 4 UAVs loitering over the target needs to be recorded separately.

Before the times can be recorded separately, the time of each individual UAVs loiter time must be recorded. A module was added called “Assign Individual Flight Times”. This module records the current simulation time (after the individual UAV has finished observing the target and before it begins the flight back to the rally point) and subtracts the simulation time when the UAV began its loiter over the target. This provides the simulation with an individual loiter time for each UAV.

The simulation already has a counter to keep track of how many UAVs are loitering over the target that gets updated whenever the number changes. This data is time stamped in the simulation.

With the individual loiter times and the number of UAVs over the target, the simulation can now separate the times into categories of how many UAVs were loitering over the target simultaneously and for how long. To do this, the simulation needs a decision module to separate the time being recorded into 1, 2, 3, or 4 UAVs. This can be seen in Figure 11 on the following page:

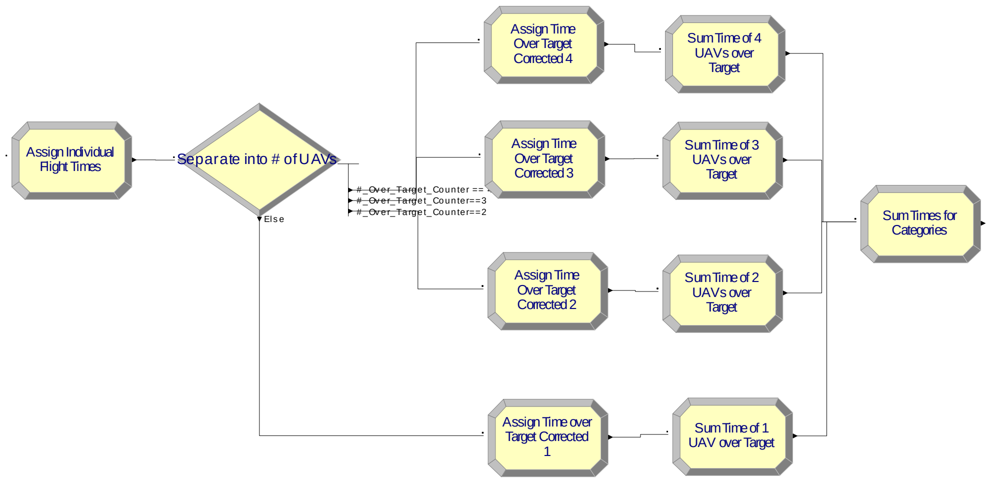


Figure 11: Implementation of theTime Observing Target Correction Factor and the Welborn Correction Factor in the Arena simulation

After being separated into separate flows within the simulation, an assignment module will use the Time Observing Target Correction Factor and the Welborn Correction Factor to create the updated time that the UAV observed the target. The assign module will then create a new variable that will represent this corrected time of observation. The Welborn Correction Factor is a formula that is applied in the Arena simulation to correct the time the target is observed when multiple rovers are observing the target. The Welborn Correction Factor in Arena can be seen below:

$$\textbf{corrected\_time\_over\_target} =$$

$$\mathbf{(1-((1-(.55+.15*BETA(1.06,1.02)))^{(\#\_UAVs\_over\_target)})) * individual\_time\_over\_target}$$

Note: BETA represents the Beta distribution

The breakdown of probabilities of observing the target during loiter by number of UAVs loitering over the target, assuming independence, is listed below:

1 Aircraft: P (1) = .55 + 0.15 * Beta (1.06, 1.02) means approximately <u>62.5%</u> of total loiter time will be collected as coverage time

2 Aircraft: P (2) = $(1-((1-(.55+.15*\text{Beta }(1.06,1.02)))^{2}))$ means approximately <u>85.9%</u> of total loiter time will be collected as coverage time

3 Aircraft: P (3) = $(1-((1-(.55+.15*\text{Beta }(1.06,1.02)))^{3}))$ means approximately <u>94.7%</u> of total loiter time will be collected as coverage time

4 Aircraft: P (4) = $(1-((1-(.55+.15*\text{Beta }(1.06,1.02)))^{4}))$ means approximately <u>98.0%</u> of total loiter time will be collected as coverage time

The entity in the simulation then travels into another assign module that adds the corrected time observing the target to a variable that represents the total time of its respective number of UAVs spent observing the target.

Finally, the separate flows converge into a module, “Sum Times for Categories”, which sums the total corrected observation times for all the categories previously mentioned and assigns the total corrected observed time to a new variable called “coverage_time”.

4.3.3 Modification to Value Added Sub-Model

The current value added sub-model acts as a switch that records time while there is one or more UAVs over the target and the operator is available to observe the video feedback. There is another part of the sub-model that includes logic that adds the last loiter time into the value added or non-value added categories using the same criteria.

This must be altered by applying the correction factors developed earlier that account for the time that the UAVs did not observe the target while loitering. Since the formula is altered depending on how many UAVs are loitering over the target, the simulation needs a means of separating the value added times every time the number of UAVs loitering over the target changes.

In order to do this, a decision module was added to the value added model as can be seen below. This module separates the value added entity into five different streams depending on a variable that keeps track of how many UAVs are over the target at any time. The first four flows all add value to the total of value added. The fifth flow screens out time periods during which there is no value being added due to there being no UAV over the target, shown below:

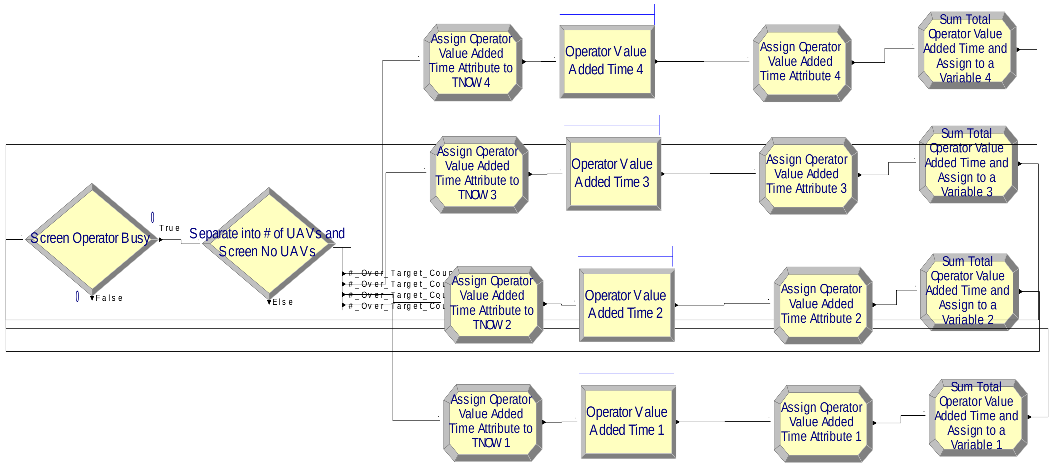


Figure 12: Modified Value Added Sub-Model

It executes the screen by looping the entity back to the original model's "Operator Busy" stream which records the time that there is no value being added by holding the entity until two conditions are met: 1) the number of UAVs loitering over the target is greater than zero and 2) the operator (represented in the simulation as a resource) is not otherwise utilized (i.e. fixing a UAV, launching a UAV, etc…). This section of the value added sub- model can be seen below:

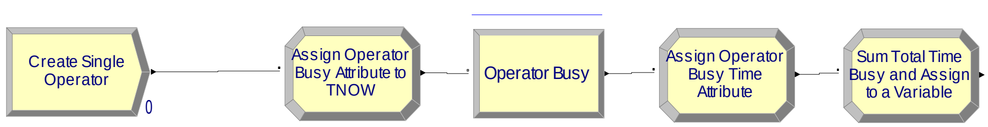


Figure 13: Value Added Create Single Operator Entity Module, Operator Busy Hold Module with Time Measuring and Time Summing Modules

The modules on either side of the "Operator Busy" Hold Module measure the amount of time that the operator spends not adding value by observing video feedback from the UAV. The last module adds each recorded time to a running total of Total Busy Time.

The evolution of the simulation shown below uses a nested loop. The criteria for exiting the inner loop, once the value starts being added, is that either the operator becomes busy or there are no more UAVs over the target. When the exit criteria are met, the entity returns to the original time assignment and hold modules listed above.

The inner loop was created to keep the model adding value but to assign different times to the value added based off of how many UAVs are over the target. More UAVs over the target at once will reduce the intermittent loss of coverage by providing less chance of failure to observe.

The inner loop has four possible streams. This represents there being up to four UAVs over the target at any time. Each of the streams has a time initiator module, a hold module, a module to assign the time of observation (after applying the correction factor) to a variable, and a total value added variable that adds the individual value added times together to get the total value added time for each iteration.

Each "Operator Value Added Time" hold module will hold the entity and scan for the condition that either the operator is busy or the number of UAVs over the target has changed. When this happens, the entity has its time that it added value recorded and added into the sum. It then loops back to the beginning of the inner loop where it will be screened against busy operators.

If the operator is busy, the entity is looped out of the inner loop. If the operator is free, the entity proceeds to the separation decision module. If the change in UAVs over the target resulted in zero UAVs over the target, the entity will exit the inner loop. Otherwise, it will be sent to the new current number of UAVs over the target.

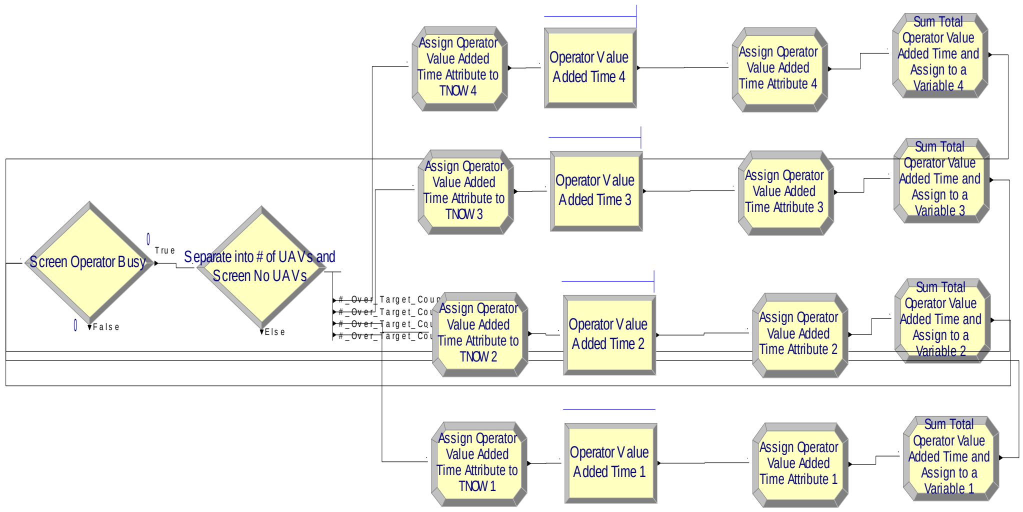


Figure 14: Modified Value Added Sub-Model

Also, the criterion for observing a target in this simulation is to have one UAV observing the target. Capt Wellbaum used 2 or more UAVs as one of his criteria[5]. This option was removed in this simulation. The “Operator Busy” and “Operator Value Added Time” hold modules, shown below, were modified by exchanging the value of one in place of two in the “scan for” criteria to represent only needing one UAV to loiter over the target while the operator is not pre-occupied in order to add value.

There is a second part to the value added sub-model that creates an entity upon completion of each replication, shown in the figure below. The decision module in this string of modules looks into the value added hold modules to see if there is any remaining value added time at the end of the replication that didn’t get added to the total due to the operation coming to an end. If there is an entity any of the value added hold modules, the time is added to the total value added time.

The final value added sub-model measures the simulation time that the entity was in the hold module. It does not give it a chance to apply the correction factor. Therefore, this was added into the original sub-model.

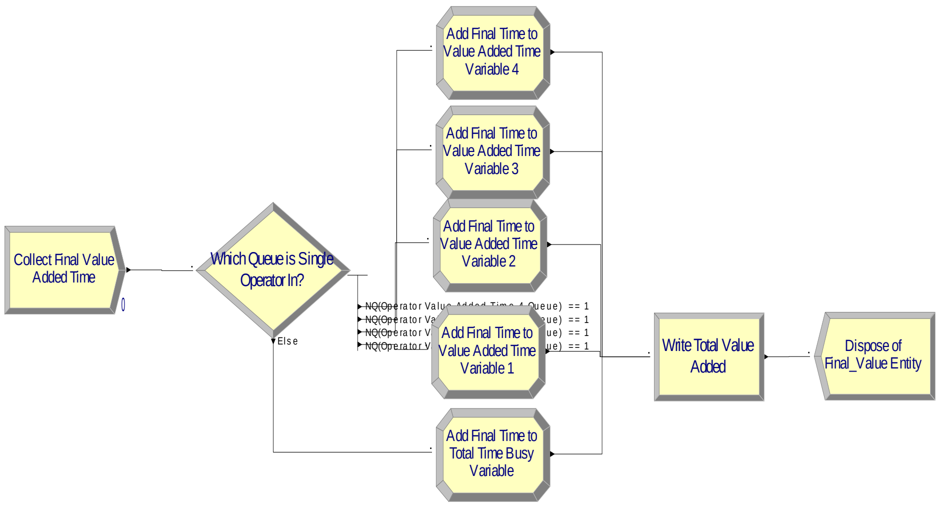


Figure 15: Modified Value Added Sub-Model End of Replication

4.3.4 Analysis of Simulation Results

To better understand the effects of the correction factors, the results of the Wellbaum simulation without correction factors will be compared to the results of the simulation with correction factors from Cottle's 2011 thesis and the correction factors arrived at in this research[6]. For the sake of isolating just the changes due to the correction factors, common random numbers will again be used for each simulation run and the same input variables will be used.

The tools used to analyze the output data are part of the Rockwell Arena Simulation software suite. The tools are the OptQuest optimization tool and the Process Analyzer tool.

OptQuest determines the optimal choice of control variables to minimize or maximize a response variable that is named as the objective variable. The user may input constraints for the optimization and set parameters for the control variables. The OptQuest tool uses three replications for each scenario. It runs a different simulation for each possible combination of control variables within the parameters set by the user. OptQuest keeps a record of the simulation resulting in the most desirable response variable.

All of the simulations run for this research use the Total Value Added Time as the objective response variable. This is the total amount of time that an OWL is loitering over the target, the target is in the field of view of an OWL, and the operator is observing the video and not otherwise utilized. The goal for the optimization program is to maximize the Total Value Added Time.

Process Analyzer was designed for quickly running and comparing multiple scenarios using multiple controls. The user specifies which simulation to run and which variables are the control and response variables. The user can then set up each desired instantiation to observe. The Process Analyzer will continuously run through all stated scenarios with the various values for the controls given by the user.

Process Analyzer runs as many replications as the user sets in the Arena simulation “Run Control”. For the purposes of this work, each simulation for each scenario is run for 100 replications. Process Analyzer then lists the mean for the 100 replications. This makes Process Analyzer a more accurate reflection of the most likely results. The results from Process Analyzer can be compared with the OptQuest results, which represent the best case scenario, to get an idea of the range of possible solutions.

The simulations that are considered modified have received not only the correction factors from this body of work but also Cottle's correction factors. Cottle reduced the total battery endurance by eight minutes for a safety factor. He added a variable for wind speed that in high wind conditions (speeds > 15 mph) further reduced the battery endurance by an additional five minutes. He increased the chance of non-routine maintenance from one percent to five percent and increased the repair time distribution from TRIA(3, 5, 10) to TRIA(4, 7, 11). Finally, the time to conduct routine maintenance was increased by 60 seconds. Each of these correction factors adds more realism to the original scenario but diminishes the amount of time over the target from the original.

It is also expected that the Time Over Target Correction Factor and Welborn Correction Factors will also reduce the amount of time that the operator is able to observe the target. Thus, the Total Value Added Time is expected to be reduced further from the original simulation's results.

There are three effects that are critical to the outcomes of the simulation runs. First, the total time that there is at least one UAV over the target. An OWL will observe the target roughly 63% of the time that it loiters overhead. Big gaps with no UAV overhead result in a loss of the 63% observation rate.

Second, for every additional OWL that is over the target at the same time, the percentage of time that gets recorded increases due to overlapping observation patterns greatly reducing the amount of intermittently lost target observation. With four OWLs loitering overhead the efficiency of observing the target increases to 99% of the loiter time, assuming the causes of the intermittent losses in target observation are independent and not caused by a single factor that has the same effect on all OWLs at one time.

The third critical factor to affect the outcome of the simulation is the amount of time that the operator is busy and cannot observe the video feedback. The more UAVs being used, the more tasks the operator has to perform that pull him or her from observing video. The operator must Launch, Retrieve and Maintain each OWL. The operator also has a 5% chance to have to have to repair an OWL for every UAV launched. This reduces the value added time by a mean of seven minutes and can take as much as 11 minutes.

These factors are all competing against each other to determine the optimal solution. Also affecting the simulation is wind speed, but separate simulations will be run for low and high wind speeds in order to further isolate this factor. High wind speeds result in a reduction of battery endurance by five minutes. This reduction in battery endurance, in turn, is expected to cause the UAV over target time to decrease and the value added time to decrease.

After analyzing the results of the long distance and short distance simulations, using independent scenarios for low and high wind, the results of the simulations will be compared to the results of the original simulation before any of the correction factors were included.

4.3.4.1 Corrected Simulation Results for Short Range, Low Wind Scenario

The first scenario for comparison will be the results of the target within radio frequency line-of-sight (LOS) range. There will be one modified model run with low wind conditions and another run with high wind conditions. This is not necessary with the original model because it has no changes for either. Variables for this scenario are defined in Table 2 below:

Table 2: Model Setup for Target within LOS Scenario

Model Setup for Target Within LOS Scenario			
Constant Variables	Value	Independent Variables	Value Range
#_OWL_Relays	0	#_of_OWL_Rovers	1 – 4
Mission_Length_Hours	8	Time_Between_Initial_Launch (Minutes)	1 – 40
Rover_Max_Range_Miles	3		
Distance_to_Target_Miles	3	Dependent_Variables	
Speed_to_Target_MPH	30	Total_Value_Added_Time	
Wind_Speed_MPH	10 (Low) 20 (High)	Total_UAV_Over_Target Time	

The optimization using Rockwell Arena's OptQuest tool can be seen in Table 3:

Table 3: OptQuest Optimized Solution with all Correction Factors Low Wind within RF Line of Sight (3 miles)

Best Solutions				
Simulation	Objective Value	Status	#_of_OWL_Rovers	Time_Between_Initial_Launch
22	296.089417	Feasible	4	32
25	291.760834	Feasible	4	38
60	289.700970	Feasible	4	29
27	289.622472	Feasible	4	31
24	288.470644	Feasible	4	33
58	288.263232	Feasible	4	27
79	288.190969	Feasible	4	39
13	287.721520	Feasible	4	37
15	287.450789	Feasible	4	36
26	286.765875	Feasible	4	35
63	286.261419	Feasible	3	19
28	286.247062	Feasible	4	30
57	286.125043	Feasible	3	16
81	285.282579	Feasible	4	28
5	285.167852	Feasible	3	21
33	284.006960	Feasible	4	34
66	283.904924	Feasible	3	13
8	283.146491	Feasible	4	40
46	282.611858	Feasible	4	26
131	282.366727	Feasible	3	14
50	282.191595	Feasible	3	9
55	281.937993	Feasible	3	24
113	281.646330	Feasible	3	33
104	281.641408	Feasible	3	22
121	281.341647	Feasible	3	29

The first OptQuest Optimization shows that during operations within radio frequency line of sight and in low wind conditions (less than or equal to 15 mph), the best outcome possible for Total Value Added Time is approximately 296 minutes. To achieve this time, OptQuest used the combination of 4 rovers with a time between initial launching of 32 minutes each.

The highest value added results alternate between using three and four OWLs with neither one providing the dominant solution. This means that optimal results can be obtained with either three or four OWLs. The difference between the top simulation and the 25^{th} simulation was a difference of 15 minutes Value Added Time.

The results of the Process Analyzer runs can be seen in Table 4 on the following page:

Table 4: Process Analyzer Results with all Correction Factors Low Wind within RF Line of Sight (3 miles)

Controls					Responses	
#_of_OWL_Rovers	Time_Between_Initial_Lau	wind_speed	Distance_to_Target_Miles	#_of_OWL_Relays	Total_Value_Added_Time	Total_UAV_Over_Target
4	1	10	3	0	266.281	466.580
4	5	10	3	0	264.770	467.397
4	10	10	3	0	280.376	469.316
4	15	10	3	0	270.099	469.428
4	20	10	3	0	279.374	469.220
4	25	10	3	0	278.927	468.362
4	30	10	3	0	286.247	468.130
4	35	10	3	0	286.766	466.420
4	40	10	3	0	283.146	460.367
3	1	10	3	0	270.378	454.677
3	5	10	3	0	268.701	455.101
3	10	10	3	0	277.914	456.875
3	15	10	3	0	274.680	459.668
3	20	10	3	0	273.922	459.704
3	25	10	3	0	280.654	459.645
3	30	10	3	0	277.828	458.160
3	35	10	3	0	274.803	455.294
3	40	10	3	0	277.860	450.498
2	1	10	3	0	252.983	426.611
2	5	10	3	0	247.289	429.098
2	10	10	3	0	243.520	432.932
2	15	10	3	0	252.056	433.900
2	20	10	3	0	248.932	435.116
2	25	10	3	0	246.699	435.062
2	30	10	3	0	253.955	432.485
2	35	10	3	0	251.462	426.025
2	40	10	3	0	256.417	423.941
1	1	10	3	0	173.648	334.315

The Process Analyzer results above represent 100 replications for each control set. These results give the mean of those hundred replications. This will be most useful for predicting the most likely outcomes of varying combinations of rovers and time between initial launch. All of the input variables are the same as those listed in the model setup table previously shown.

Mean times will let us know the value that is being added to our objective variable by increasing the number of OWLs. The mean times for value added results follow:

1) 4 OWLs – 277 minutes (4 hours and 37 minutes)
2) 3 OWLs – 248 minutes (4 hours and 8 minutes)
3) 2 OWLs – 250 minutes (4 hours and 10 minutes)
4) 1OWL – 174 minutes (2 hours and 54 minutes)

The average time to be gained from increasing the number of OWLs goes up 26 and 24 minutes respectively for 2 and 3 OWLs versus using a single OWL. There is added value of 103 minutes for using 4 OWLs compared to 1 OWL. This is not taking proper Tactics, Techniques, and Procedures for times between initial launches. If proper Time Between Initial Launch TTPs are adhered to, the results will be as follows:

1) 4 OWLs with TBIL 35 minutes – 287 minutes (4 hours and 47 minutes)
2) 3 OWLs with TBIL 25 minutes – 281 minutes (4 hours and 41 minutes)
3) 2 OWLs with TBIL 40 minutes – 256 minutes (4 hours and 16 minutes)
4) 1 OWL – 174 minutes (2 hours and 54 minutes)

This means that when the OWLs are properly utilized, there is a difference of 82, 107, and 113 minutes for 2, 3, and 4 OWLs respectively when compared to using 1 OWL.

Based on these results we see continued improvement in Value Added Time for each OWL added into the scenario. The returns for each OWL, assuming the optimal TBILs are always adhered to, diminish quickly so that the difference between 3 and 4 OWLs is only 6 minutes compared to a difference of 82 minutes for the first additional OWL (for a total of 2 OWLs).

Statistical analysis was used to determine whether the differing value added times resulting from using the TTPs recommended or not using the TTPs is statistically significant.

The statistical method to compare the two samples was the paired-t test. The formula used in the paired-t test can be seen in Equation 1 below:

$$\left(\bar{\theta}_1 - \bar{\theta}_2\right) \pm t_{\alpha/2,v} = \left(R-1\right)\frac{s_D}{\sqrt{R}} \qquad \text{(Eq. 1)}$$

Where $\bar{\theta}$ is the mean of the MOP, S_D is the standard deviation, and R is the number of replications. The means of the total value-added time when using four OWLs with no TTPs (i.e. the OWLs were thrown at random times between 1 and 40) was compared to the mean of the total value-added time when four OWLs were flown using a TBIL of 35 minutes. Nine hundred replications were run for each sample.

The results of this paired-t test can be seen in Table 5:

Table 5: Two Sample for Means Paired-t Test with all Correction Factors Low Wind within RF Line of Sight

	Variable 1	*Variable 2*
Mean	277.331888	285.7239203
Variance	2764.711865	2230.175806
Observations	900	900
Pearson Correlation	0.00243895	
Hypothesized Mean Difference	0	
df	899	
t Stat	-3.566586349	
P(T<=t) one-tail	0.000190375	
t Critical one-tail	1.646550346	
P(T<=t) two-tail	0.000380751	
t Critical two-tail	1.962606226	

Since the P(T<=t) is less than .05, we can reject the H_0 and conclude that, on average, using the recommended TBIL TTPs creates more value added than launching the UAVs at random.

If a unit had 4 OWLs and needed to monitor a target less than three miles away with wind speeds equal to or less than 15 mph, the optimal solution would be to use 4 OWLs and to launch them 35 minutes apart. The resulting Value Added Time for an 8 hour mission will be, on average, 4 hours and 47 minutes.

4.3.4.2 Corrected Simulation Results for Short Range, High Wind Scenario

The next scenario mirrors the last scenario in every way except that low wind speeds (10 mph) are used instead of high wind speeds (20 mph). This should result in a reduced battery endurance and, therefore, less value added time. It is necessary, however, to understand how this will affect the overall simulation.

The OptQuest results for the modified simulation using a high wind variable can be seen in Table 6 below:

Table 6: OptQuest Optimized Solution with all Correction Factors High Wind within RF Line of Sight

Best Solutions				
Simulation	Objective Value	Status	#_of_OWL_Rovers	Time_Between_Initial_Launch
4	271.969681	Feasible	4	36
18	270.783897	Feasible	4	37
84	269.249679	Feasible	3	31
3	269.235719	Feasible	4	31
22	268.373236	Feasible	4	33
80	268.163500	Feasible	3	32
20	267.987297	Feasible	4	30
50	267.908826	Feasible	3	26
17	267.364724	Feasible	4	34
68	267.119494	Feasible	3	23
73	266.515758	Feasible	4	24
37	265.926511	Feasible	4	38
60	265.794287	Feasible	3	17
25	264.783393	Feasible	4	35
88	264.752823	Feasible	3	16
19	264.211407	Feasible	4	32
120	264.127258	Feasible	4	23
74	264.049776	Feasible	3	14
5	263.816061	Feasible	4	39
6	263.746420	Feasible	4	40
62	263.657604	Feasible	3	20
61	263.653422	Feasible	3	19
41	263.308454	Feasible	3	28
44	263.127344	Feasible	3	27
42	262.369134	Feasible	3	18

The top 25 results, according to OptQuest, (see above) range from 262 minutes to 272 minutes. The top results alternate between using three or four OWLs with the number one result coming from using 4 OWLs with a TBIL of 36 minutes.

The results of the Process Analyzer tool using the same scenario can be seen in Table 7 on the following page:

Table 7: Process Analyzer Results with all Correction Factors High Wind Within RF Line of Sight

Controls				Responses	
#_of_OWL_R	Time_Betwe	wind_speed	Distance_to_	Total_Value_	Total_UAV_
4	1	20	3	254.335	463.393
4	5	20	3	242.213	465.122
4	10	20	3	254.997	465.789
4	15	20	3	251.817	467.194
4	20	20	3	255.962	466.802
4	25	20	3	260.334	465.412
4	30	20	3	267.987	462.364
4	35	20	3	264.783	459.376
4	40	20	3	263.746	453.654
3	1	20	3	255.437	450.916
3	5	20	3	254.713	452.444
3	10	20	3	256.218	453.751
3	15	20	3	260.777	455.646
3	20	20	3	263.658	455.975
3	25	20	3	257.349	454.522
3	30	20	3	261.494	452.669
3	35	20	3	254.609	447.220
3	40	20	3	253.085	443.476
2	1	20	3	243.227	419.609
2	5	20	3	244.739	422.233
2	10	20	3	249.813	423.583
2	15	20	3	239.630	423.559
2	20	20	3	251.893	424.261
2	25	20	3	249.916	423.398
2	30	20	3	240.897	418.330
2	35	20	3	241.513	415.342
2	40	20	3	239.215	413.194
1	1	20	3	158.692	320.170

The mean times for the value added times broken down by the number of OWLs used are as follows:

1) 4 OWLs – 257 minutes (4 hours and 17 minutes)
2) 3 OWLs – 257 minutes (4 hours and 17 minutes)
3) 2 OWLs – 245 minutes (4 hours and 5 minutes)
4) 1 OWL – 159 minutes (2 hours and 39 minutes)

This means that an operator working in high wind conditions and launching at random can achieve equivalent benefits from either three or four OWLs and would be expected to achieve 257 minutes (4 hours and 17 minutes) of value added time over an eight hour mission.

Applying proper TBIL TTPs will result in more value added time. The number of OWLs and their respective optimal TBILs are listed below:

1) 4 OWLs with TBIL 30 minutes – 268 minutes (4 hours and 28 minutes)
2) 3 OWLS with TBIL 20 minutes – 264 minutes (4 hours and 24 minutes)
3) 2 OWLS with TBIL 20 minutes – 252 minutes (4 hours and 12 minutes)
4) 1 OWL – 159 minutes (2 hours and 39 minutes)

The best time expected for the value added time is 19 minutes less in high wind than in low wind. By using Common Random Numbers and changing only the one variable, it can be determined that the 19 minute loss of value added time can be directly attributed to the effects of the high wind speed.

Again, we see a diminishing increase in value added time to a max with four OWLs. In order to achieve the best results in a short distance (3 miles away) stationary target in high wind conditions, the operator will launch all four OWLs with 30 minutes in between each launch and will achieve 268 minutes of value added time out of a 480 minute mission.

The statistical significance of the difference between the means of 4 UAVs thrown at random and 4 UAVs thrown at 30 minutes between initial launch must be determined. The paired-t test is shown in Table 8:

Table 8: Two Sample for Means Paired-t Test with all Correction Factors High Wind within RF Line of Sight

	Variable 1	*Variable 2*
Mean	265.5089382	256.6617209
Variance	2426.802262	2476.695161
Observations	300	300
Pearson Correlation	0.158051831	
Hypothesized Mean Difference	0	
df	299	
t Stat	2.384896613	
P(T<=t) one-tail	0.008853479	
t Critical one-tail	1.649965768	
P(T<=t) two-tail	0.017706958	
t Critical two-tail	1.967929605	

The probability of T being less than or equal to t is less than the .05 threshold. Therefore, the TBIL TTPs make a statistically significant difference.

4.3.4.3 Results using Original Simulation for Short Range Scenario

The next scenario will use the same input variables but will run on the original simulation. This will show the difference in results caused by the modifications made to the simulation. There will only be one short distance scenario because the original simulation did not take into effect the wind speeds. The OptQuest results for the original simulation can be seen in Table 9 below:

Table 9: OptQuest Optimized Solution Original Simulation within RF Line of Sight

Best Solutions			
Objective Value	Status	#_of_OWL_Rovers	Time_Between_Initial_Launch
406.386509	Feasible	2	34
405.749560	Feasible	2	37
405.663958	Feasible	2	32
405.555474	Feasible	2	35
405.185344	Feasible	2	36
405.093269	Feasible	2	33
405.077255	Feasible	2	28
405.071116	Feasible	2	31
405.058723	Feasible	2	30
404.899340	Feasible	2	38

As can be seen in the OptQuest results above, the top ten solutions range from 405 minutes (6 hours and 44 minutes) to 406 minutes (6 hours and 45 minutes). All of the top ten optimized alternatives involve using 2 OWLs. The Process Analyzer results can be seen in Table 10 on the following page:

Table 10: Process Analyzer Results for Original Simulation within RF Line of Sight

Controls			Responses	
#_of_OWL_Rovers	Time_Between_Initial_Lau	Distance_to_Target_Miles	Total_Value_Added_Time	Total_UAV_Over_Target
4	1	3	368.575	471.625
4	5	3	368.877	471.405
4	10	3	370.569	472.892
4	15	3	371.147	472.720
4	20	3	372.906	472.398
4	25	3	375.156	472.498
4	30	3	378.918	471.620
4	35	3	380.646	471.484
4	40	3	379.356	470.070
3	1	3	390.799	461.392
3	5	3	390.997	458.376
3	10	3	392.219	461.736
3	15	3	393.595	462.469
3	20	3	396.238	467.459
3	25	3	397.220	469.175
3	30	3	397.386	467.541
3	35	3	396.860	463.641
3	40	3	397.009	463.503
2	1	3	397.133	432.373
2	5	3	397.143	431.609
2	10	3	398.324	434.597
2	15	3	401.104	436.655
2	20	3	404.287	439.586
2	25	3	403.687	439.303
2	30	3	405.059	439.639
2	35	3	405.555	440.200
2	40	3	403.755	440.534
1	1	3	360.405	360.405

The mean times for the value added times broken down by the number of OWLs used are as follows:

1) 4 OWLs – 374 minutes (6 hours and 14 minutes)
2) 3 OWLs – 395 minutes (6 hours and 35 minutes)
3) 2 OWLs – 402 minutes (6 hours and 42 minutes)
4) 1 OWL – 360 minutes (6 hours)

If the operator launched the OWLs at random, the original model with no correction factors gives the greatest value added when using two OWLs. The value added time increases by 42 minutes when flying two OWLs as opposed to one OWL. Every OWL added after that results in a decreased total value added time.

Using proper TBIL TTPs should again lead to improved value added times. The number of OWLs and their respective optimal TBILs are listed below:

1) 4 OWLs with TBIL 35 minutes – 381 minutes (6 hours and 21 minutes)
2) 3 OWLS with TBIL 40 minutes – 397 minutes (6 hours and 37 minutes)
3) 2 OWLS with TBIL 35 minutes – 406 minutes (6 hours and 46 minutes)
4) 1 OWL – 360 minutes (6 hours)

Thus, using proper TBIL TTPs, the operator would use 2 OWLs with 35 minutes TBIL to achieve 406 minutes of total value added time out of a 480 minute mission time. The modified model resulted in a total value added time that is 138 minutes less in high wind and 119 minutes less in low wind than the original model. That is a 34% and 29% reduction respectively.

A paired-t test was conducted to determine statistical significance. The probability of T being less than or equal to t is lower than .05. Therefore, the means of the launches using TBIL TTPs is statistically different from the mean when the UAVs are launched at random. The results of the paired-t test are shown in Table 11:

Table 11: Two Sample for Means Paired-t Test for Original Simulation within RF Line of Sight

	Variable 1	*Variable 2*
Mean	407.1757675	400.9539896
Variance	121.8961845	192.3027886
Observations	99	99
Pearson Correlation	-0.078413304	
Hypothesized Mean Difference	0	
df	98	
t Stat	3.366192821	
P(T<=t) one-tail	0.000544852	
t Critical one-tail	1.660551218	
P(T<=t) two-tail	0.001089705	
t Critical two-tail	1.984467404	

This is to be expected with every correction factor diminishing the returns of the total value added time with no correction factors to the contrary. What was more difficult to predict was the affect on the number of OWLs in the optimal solution. Why did the original simulation determine that 2 OWLs would be better than the 4 OWLs that each of the modified models concluded?

The most likely answer is that the original simulation had such large advantages from extended battery endurance and the capture rate of 100% for the loiter time as time that the target was observed. The original simulation could observe 85% of the time with just 2 OWLs. This left little room for improvement. Since there is no advantage in the original simulation for having more than one OWLs flying over the target, the extra OWLs resulted in a waste of time for the operator that yielded relatively little advantage in the total added value time.

4.3.4.4 Corrected Simulation Results Long Range, Low Wind Scenario

The next set of scenarios will all be long distance. Long distance in this simulation will be 5 miles. This will require the OWLs to be split up into rover/relay pairs because the target is beyond radio frequency line of sight. These scenarios are expected to yield a much lower total value added time because the flight times to and from the target are longer, the max number of rovers to loiter over the target is two, and the operator must expend the amount of time necessary to take care of four OWLs while only getting the added observation time from the one or two rovers loitering over the target.

Each of the following scenarios will define its parameters using Table 12 on the next page:

Table 12: Model Setup for Target Beyond LOS Scenario

Model Setup for Target Beyond LOS Scenario			
Constant Variables	Value	Independent Variables	Value Range
Mission_Length_Hours	8	#_of_OWL_Rovers	1 - 2
Rover_Max_Range_Miles(RF)	3	#_of_OWL_Relays	1 - 2
Speed_to_Target_MPH	30	Time_Between_Initial_Launch (Minutes)	1 - 40
Wind_Speed_MPH	10 (Low) 20 (High)		
Distance_to_Target_Miles	5		
Dependent_Variables			
Total_Value_Added_Time			
Total_UAV_Over_Target Time			

In Table 13 on the following page, we see the results from the OptQuest running the above variables using low wind speed:

Table 13: OptQuest Optimized Solution with all Correction Factors Low Wind Beyond RF Line of Sight

Best Solutions				
Objective Value	Status	#_of_OWL_Relays	#_of_OWL_Rovers	Time_Between_Initial_Launch
154.106906	Feasible	2	2	32
153.415707	Feasible	2	2	8
151.543368	Feasible	2	2	24
151.459621	Feasible	2	2	31
151.380727	Feasible	2	2	27
151.176292	Feasible	2	2	33
150.024149	Feasible	2	2	34
149.194176	Feasible	2	2	9
148.934666	Feasible	2	2	28
148.843240	Feasible	2	2	30
148.603214	Feasible	2	2	18
148.270144	Feasible	2	2	29
148.220891	Feasible	2	2	21
148.177639	Feasible	2	2	26
147.928703	Feasible	2	2	17
147.845057	Feasible	2	2	25
147.726071	Feasible	2	2	39
147.294573	Feasible	2	2	35
147.265262	Feasible	2	2	10
146.902814	Feasible	2	2	20
146.570463	Feasible	2	2	23
145.256029	Feasible	2	2	22
145.190649	Feasible	2	2	19
144.094508	Feasible	2	2	40
143.641871	Feasible	2	2	16

The results of the OptQuest show that the highest value added is 154 minutes. This is achieved by using 2 rovers and 2 relays and launching with a TBIL of 32 minutes. The Process Analyzer results for this scenario are shown in Table 14:

Table 14: Process Analyzer Results using all Correction Factors Low Wind Beyond RF Line of Sight

Controls					Responses	
#_of_OWL_R	Time_Betwe	wind_speed	Distance_to_	#_of_OWL_R	Total_Value_	Total_UAV_
2	1	10	5	2	142.238	301.859
1	1	10	5	1	87.834	203.829
2	5	10	5	2	139.857	303.158
2	10	10	5	2	147.265	307.742
2	15	10	5	2	140.528	312.659
2	20	10	5	2	146.903	318.306
2	25	10	5	2	147.845	321.546
2	30	10	5	2	148.843	321.737
2	35	10	5	2	147.295	322.145
2	40	10	5	2	144.095	321.679

The mean of the Process Analyzer results above broken down by number of OWLs are as follows:

1) 2 Rover/Relay Pairs – 145 minutes (2 hours and 25 minutes)
2) 1 Rover/Relay Pair – 88 minutes (1 hour and 28 minutes)

If the operator were to launch each rover/relay pair randomly with no attention being paid to TBIL, the operator would achieve on average 145 minutes of value added time by using 2 rover/relay pairs. If the operator used the TBIL TTPs, the value added times will increase as seen below:

1) 2 Rover/Relay Pairs with TBIPL 30 minutes – 149 minutes (2 hours and 29 minutes)
2) 1 Rover/Relay Pair – 88 minutes (1 hour and 28 minutes)

Before looking further into this data, it needs to be determined whether there is a significant difference between the means of using no particular TBIL or using the recommended TBIL TTP. Using a paired-t test again results in Table 15:

Table 15: Two Sample for Means Paired-t Test with all Correction Factors Low Wind beyond RF Line of Sight

	Variable 1	*Variable 2*
Mean	148.8432401	148.7126833
Variance	3208.55359	3234.79012
Observations	100	100
Pearson Correlation	0.005748217	
Hypothesized Mean Difference	0	
df	99	
t Stat	0.016311573	
P(T<=t) one-tail	0.493509326	
t Critical one-tail	1.660391157	
P(T<=t) two-tail	0.987018653	
t Critical two-tail	1.9842169	

The probability of T being less than or equal to t is high in this comparison. This means that the comparison fails to reject the H_0 hypothesis and there is no statistical difference, on average, between the two means.

This makes it clear that it is preferable to use 2 rover/relay pairs in long distance, low wind scenarios. It adds over one additional hour to the total value added time when compared to the single rover/relay pair. When compared to our short distance, low wind scenario we achieve 2 hours and 18 minutes less total value added time. This is a 48%

reduction. This shows how much more effective the OWLs are at short distance than long distance.

Therefore, the operator in this scenario should use 2 rover/relay pairs, but it is not important how long to wait between launching each pair because the difference between the optimal TBIL and the mean of all TBILs is not statistically significant.

4.3.4.5 Corrected Simulation Results for Long Range, High Wind Scenario

The same simulation will now be run with high winds speeds (>15 mph) to determine the effects of wind speed on long distance flights. The results of this OptQuest optimization can be seen in Table 16:

Table 16: OptQuest Optimized Solution with all Correction Factors High Wind Beyond RF Line of Sight

Best Solutions				
Objective Value	Status	#_of_OWL_Relays	#_of_OWL_Rovers	Time_Between_Initial_Launch
147.493217	Feasible	2	2	12
144.777171	Feasible	2	2	15
143.720483	Feasible	2	2	23
143.546646	Feasible	2	2	25
142.516478	Feasible	2	2	10
142.041143	Feasible	2	2	20
141.488424	Feasible	2	2	9
141.471135	Feasible	2	2	24
140.982452	Feasible	2	2	22
140.372105	Feasible	2	2	33
139.746591	Feasible	2	2	17
139.557419	Feasible	2	2	28
139.459442	Feasible	2	2	14
139.236099	Feasible	2	2	13
139.138286	Feasible	2	2	19
138.918106	Feasible	2	2	16
138.669841	Feasible	2	2	11
138.096544	Feasible	2	2	30
138.003719	Feasible	2	2	18
137.955817	Feasible	2	2	26
137.724331	Feasible	2	2	8
137.229072	Feasible	2	2	31
136.981399	Feasible	2	2	21
136.697624	Feasible	2	2	32
136.037017	Feasible	2	2	7

The same scenario was put into OptQuest with a wind speed of 20 mph instead of 10 mph to analyze the results of high winds on long distance rover/relay pairs. The range in the top ten results range from 136 minutes to 147 minutes. The optimal results all use 2 rover/relay pairs. The optimal TBIPL for two rover/relay pairs is 12 minutes. This is feasible for a OWL operator. The Process Analyzer results for the same scenario can be seen in Table 17 below:

Table 17: Process Analyzer Results using all Correction Factors High Wind Beyond RF Line of Sight

Controls					Responses	
#_of_OWL_R	Time_Betwe	wind_speed	Distance_to_	#_of_OWL_R	Total_Value_	Total_UAV_
2	1	20	5	2	132.066	286.021
1	1	20	5	1	86.952	188.210
2	5	20	5	2	133.278	288.903
2	10	20	5	2	142.516	294.276
2	15	20	5	2	144.777	296.496
2	20	20	5	2	142.041	297.935
2	25	20	5	2	143.547	300.868
2	30	20	5	2	138.097	303.300
2	35	20	5	2	132.233	302.514
2	40	20	5	2	127.552	299.046

The means from the Process Analyzer results for the modified simulation at a distance of 5 miles to target under high wind conditions are broken down below:

1) 2 Rover/Relay Pairs – 137 minutes (2 hours and 17 minutes)
2) 1 Rover/Relay Pair – 87 minutes (1 hour and 27 minutes)

If thrown at random, the results above suggest that the operator should use 2 rover/relay pairs and will achieve 137 minutes of value added time. If the operator utilizes the suggested TBIPL TTPs, the operator can achieve the following results:

1) 2 Rover/Relay Pairs with TBIPL 15 minutes – 145 minutes (2 hours and 25 minutes)
2) 1 Rover/Relay Pair – 87 minutes (1 hour and 27 minutes)

The difference between these scenarios is a reduction of 4 minutes total value added time when using optimal TTPs in high wind versus low wind. There are only eight minutes to be gained by using the TBIPL TTPs versus launching them randomly as long as 2 rover/relays are used.

To determine if this small difference is statistically significant, the data analysis tool in excel was used. The results can be seen in Table 18:

Table 18: Two Sample for Means Paired-t Test with all Correction Factors High Wind beyond RF Line of Sight

	Variable 1	*Variable 2*
Mean	137.349154	135.867227
Variance	3207.023097	3382.07193
Observations	900	900
Pearson Correlation	0.027469337	
Hypothesized Mean Difference	0	
df	899	
t Stat	0.555368639	
P(T<=t) one-tail	0.289390352	
t Critical one-tail	1.646550346	
P(T<=t) two-tail	0.578780704	
t Critical two-tail	1.962606226	

The probability that T is less than or equal to t for two-tails is greater than the .05 threshold. Therefore, the effects of the TBIL TTPs at long range during high winds are not statistically different from the mean of launching the rover / relay pairs at random.

4.3.4.6 Results using Original Simulation for Long Range Scenario

The last scenario to simulate will be the original simulation modeling a long range scenario. The results of the optimization can be seen in Table 19:

Table 19: OptQuest Optimized Solution Original Simulation Beyond RF Line of Sight

Best Solutions				
Objective Value	Status	#_of_OWL_Relays	#_of_OWL_Rovers	Time_Between_Initial_Launch
312.709400	Feasible	2	2	36
312.407458	Feasible	2	2	40
312.393033	Feasible	2	2	35
312.337349	Feasible	2	2	37
312.158571	Feasible	2	2	39
312.110507	Feasible	2	2	34
312.051276	Feasible	2	2	38
311.486421	Feasible	2	2	33
310.213489	Feasible	2	2	32
310.002721	Feasible	2	2	30

The OptQuest results show that 2 rover/relay pairs dominate 1 rover/relay pair for every TBIPL. The top ten results range from 310 to 313 minutes. The optimal TBIPL, according to the OptQuest is 36 minutes. This will result in a value added time of 313 minutes.

The Process Analyzer results for this scenario are shown in Table 20 on the following page:

Table 20: Process Analyzer Results using Original Simulation Beyond RF Line of Sight

Controls				Responses	
#_of_OWL_Rovers	Time_Between_Initial_Lau	Distance_to_Target_Miles	#_of_OWL_Relays	Total_Value_Added_Time	Total_UAV_Over_Target
2	1	5	2	296.398	332.929
2	5	5	2	293.648	326.671
2	10	5	2	292.412	325.097
2	15	5	2	295.492	327.926
2	20	5	2	291.534	325.478
2	25	5	2	297.654	332.408
2	30	5	2	300.153	337.621
2	35	5	2	302.308	340.593
2	40	5	2	308.021	346.975
1	1	5	1	238.516	240.643

The respective means for the value added times are:

1) 2 Rover/Relay Pairs – 297 minutes (4 hours and 57 minutes)

2) 1 Rover/Relay Pair – 239 minutes (3 hours and 59 minutes)

If the OWLs were launched at random, the original simulation predicts 297 minutes of value added time using 2 rover/relay pairs. If the TBIPL TTPs are used the results will be altered to the following:

1) 2 Rover/Relay Pairs with TBIPL 40 minutes – 308 minutes (5 hours and 8 minutes)

2) 1 Rover/Relay Pair – 239 minutes (3 hours and 59 minutes)

The statistical significance has been checked using the paired-t test. The results of this test are shown in Table 21:

Table 21: Two Sample for Means Paired-t Test for Original Simulation beyond RF Line of Sight

	Variable 1	*Variable 2*
Mean	312.2099161	297.5424219
Variance	893.6530613	1650.861617
Observations	100	100
	-	
Pearson Correlation	0.013839816	
Hypothesized Mean Difference	0	
df	99	
t Stat	2.888704446	
P(T<=t) one-tail	0.002376058	
t Critical one-tail	1.660391157	
P(T<=t) two-tail	0.004752117	
t Critical two-tail	1.9842169	

The data above shows that the difference in means for the original simulation between the mean of value added when launched at random and the value added when launched according to the recommended TBIL TTPs is statistically significant.

Using the TBIPL TTPs, the operator manages to gain an additional 11 months. The modified simulation resulted in a reduction of 163 minutes for high winds and 159 minutes for low winds in comparison to the original simulation. This is a 53% and 52% reduction, respectively.

V. Conclusions and Recommendations

5.1 Conclusions

This thesis integrated multiple simulation and analysis tools in order to better predict the outcome of a single operator using multiple UAVs with varying Tactics, Techniques, and Procedures applied to the Time Between Initial Launches (or Paired Launches).

The results have multiple useful applications. Optimal TTPs will be recommended to use in military operations using small Ravens with multiple UAVs used by one operator.

Also, the simulation more effectively estimates the amount of time that an operator will be able to observe data from OWLs conducting reconnaissance. This will help with mission planning and future cost analyses to determine the proper number of UAVs to be purchased and issued to units.

There were two goals in this research. The first was to develop a correction factor that will make the predictions of Value Added Time more realistic due to loss of the target within the camera's field of view during loiter.

This was done by creating two correction factors. The first is the Time Observing Target Correction Factor. The Time Over Target Correction Factor is aspplied when a single UAV is loitering over the target. This arena code can be seen below:

corrected_time_over_target =

(0.55 + 0.15 * BETA(1.06, 1.02)) * time_over_target

Note: where BETA represents the Beta distribution

The second correction factor is the Welborn Correction Factor. This is the factor used when multiple UAVs are loitering simultaneously around the target. The Welborn Correction Factor can be seen below:

$$\textbf{corrected\_time\_over\_target} =$$

$$\textbf{(1-((1-(.55+.15*BETA(1.06,1.02)))}^{\textbf{(\#\_UAVs\_over\_target)}}\textbf{)) * individual\_time\_over\_target}$$

Note: BETA represents the Beta distribution

These two correction factors were integrated into the simulation to improve the accuracy and realism of the simulation when predicting the outcomes of various TTPs applied to various scenarios.

The second goal of this thesis was to develop TTPs for the military to use to optimize the benefits received from the use of multiple rovers with one operator. The recommended TTPs are summarized in Table 22 on the next page:

Table 22: Summary Results (8 Hour Mission)

Scenario	Recommended # of UAVs (Rovers/Relays)	Recommended TBIL / TBIPL	Expected Value Added Time with TTPs	Expected Value Added Time without TTPs	Max Value Added Time (TBIL or TBIPL)
3 Miles, Winds <= 15 mph	**4 / 0**	**35 min**	**287 min**	**277 min**	**296 min (32 min)**
3 Miles, Winds > 15mph	**4 / 0**	**30 min**	**257 min**	**268 min**	**272 min (36 min)**
5 Miles, Winds <= 15 mph	**2 / 2**	**n/a**	**n/a**	**145 min**	**154 min (32 min)**
5 Miles, Winds > 15 mph	**2 / 2**	**n/a**	**n/a**	**137 min**	**147 min (12 min)**
Original Simulation within LOS	**2 / 0**	**35 min**	**406 min**	**402 min**	**406 min (34 min)**
Original Simulation beyond LOS	**2 / 2**	**40 min**	**308 min**	**297 min**	**313 min (2 min)**

Using TBIL TTPs for is useful for short range scenarios. The TTPs above should be used in such cases. However, the TBIL TTPs lose their statistical significance when operating at longer range. In such cases, the deciding factor should be based solely on operational preferences. Longer TBILs might be easier for the operator, whereas shorter TBILs will initially result in optimal surveillance until completion of the first sortie.

The launch times recommended in Table 17 above are feasible for an operator. For routine surveillance, the above numbers of UAVs and Time Between Initial Launches should be used. For other contingencies, knowledge of the effects of the simulation will be useful for TTPs in such cases.

For example, the TTPs recommended above are optimized for routine continued surveillance over eight hours. What if a firefight arises and it is more important to maximize the percentage of time that the target is observed as soon as possible? What if the mission will not last eight hours? What if the first hour is critically important and the last seven hours are much less important? In these cases, the TTP could be to launch every UAV with as small a TBIL as possible because it is more important to get 99% of the time observing target for the first half hour than to have the optimal time observing target over an eight hour period.

5.2 Recommendations for Future Work

There are areas of improvement in other fields that could play an important part in the validity of the simulation. One of these areas is human factors. The current simulation assumes that a human can observe the video transmission 100% of the time. This is clearly not the case. There are many issues that would affect the operator's ability to effectively monitor the various simultaneous transmissions under various conditions. This is an extremely rich area for further calibration of the simulation.

While this study sought to find the best TTPs for operating multiple UAVs with a single operator in varying operational scenarios and conditions, another interesting question that came up was whether it would be worth the money. A cost analysis should be done to determine if the value added by additional UAVs supports the monetary cost of each additional UAV. Often, there are gains had by employing a fourth OWL over the first three OWLs, but the diminished return is not substantial enough to be worth the additional $35,000 that each UAV costs.

In addition to potential areas of improvement that would require experience in another specialization, there are a few simulation aspects that could be improved by the next round of simulation calibrations. These are an improved wind speed correction factor, a correction factor for the effects of elevation, and a correction factor for the effects of varying speeds or distances.

The wind correction factor currently used is very simplistic. It relies on a single switch between high winds and low winds. A scale should be developed that accounts for the effects on battery life and the effects on the percent of time that the UAV loiters over the target that the target will be observed.

Elevation plays a huge effect on the size of the footprint from the camera. Further work can be done to determine the effects of elevation in the simulation and its effects on the percent of time that the UAV loiters over the target that the target will be observed.

The loiter radius, roll of the UAV, and speed of the aircraft should also receive further calibration in order to further the realism and accuracy of the simulation in mission planning.

In the simulation looked at in this research, the speed of flight for the UAV was fixed at 30 mph. The effects of changing speeds should be looked at in future simulation calibrations. Also, the distance to target was fixed for each scenario. Three miles to target was used to achieve an all rover scenario and five miles to target was used to require a rover/relay scenario. In future calibrations, this could be optimized according to a sliding scale for speed and distance.

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Appendix A: ARENA Model Images

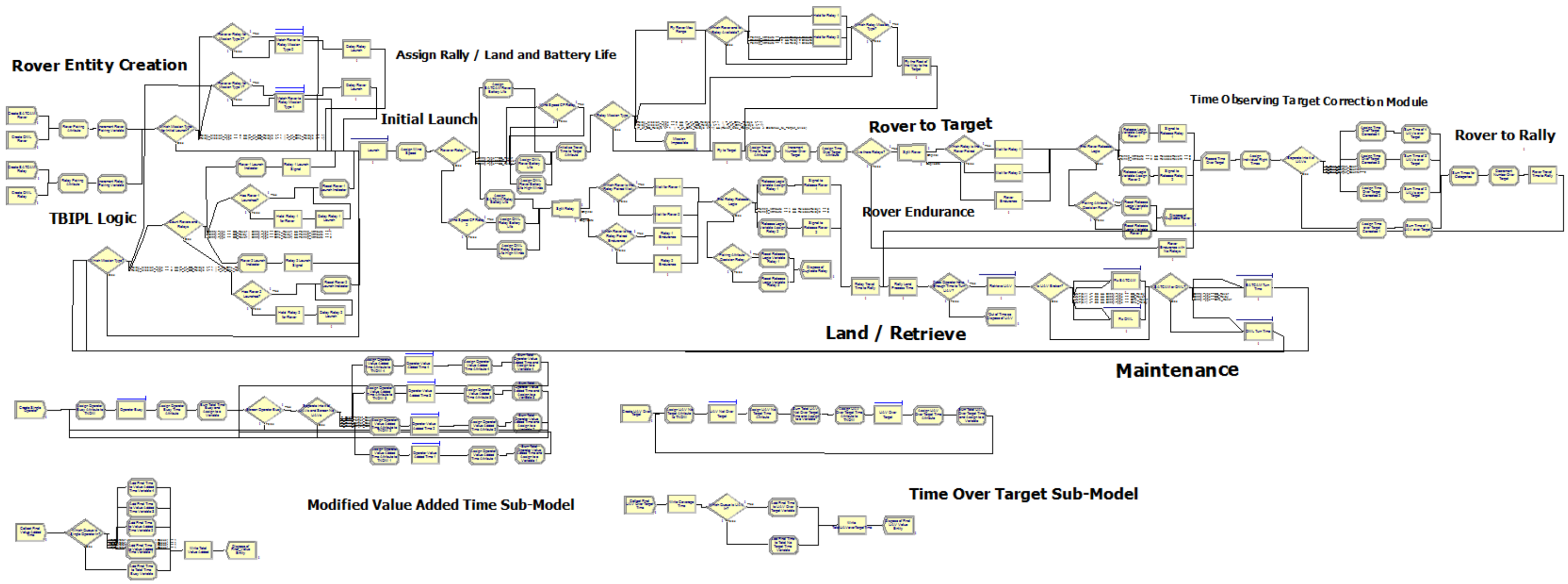

Figure 16: Full Arena Model with Accompanying Sub-models

The Moving Target sub-model has been removed from the original because it was not utilized in this study.

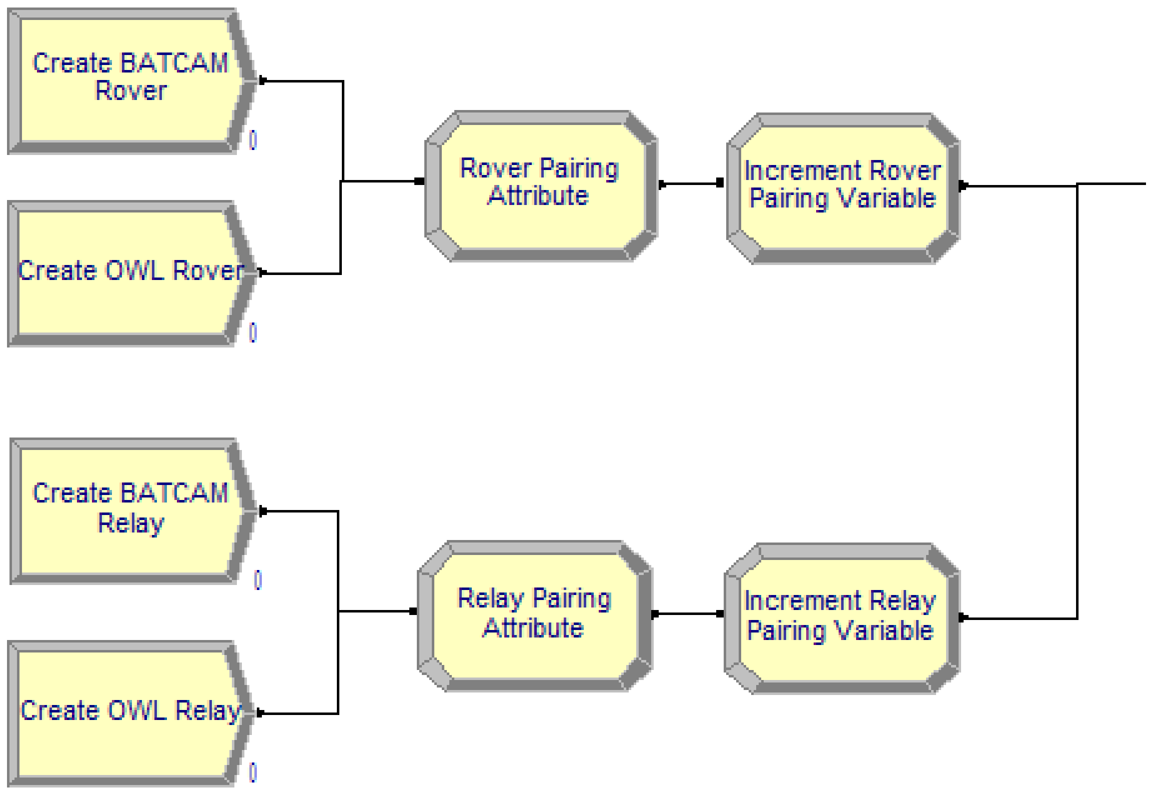

Figure 17: Rover Entity Creation and Rover Pairing Logic

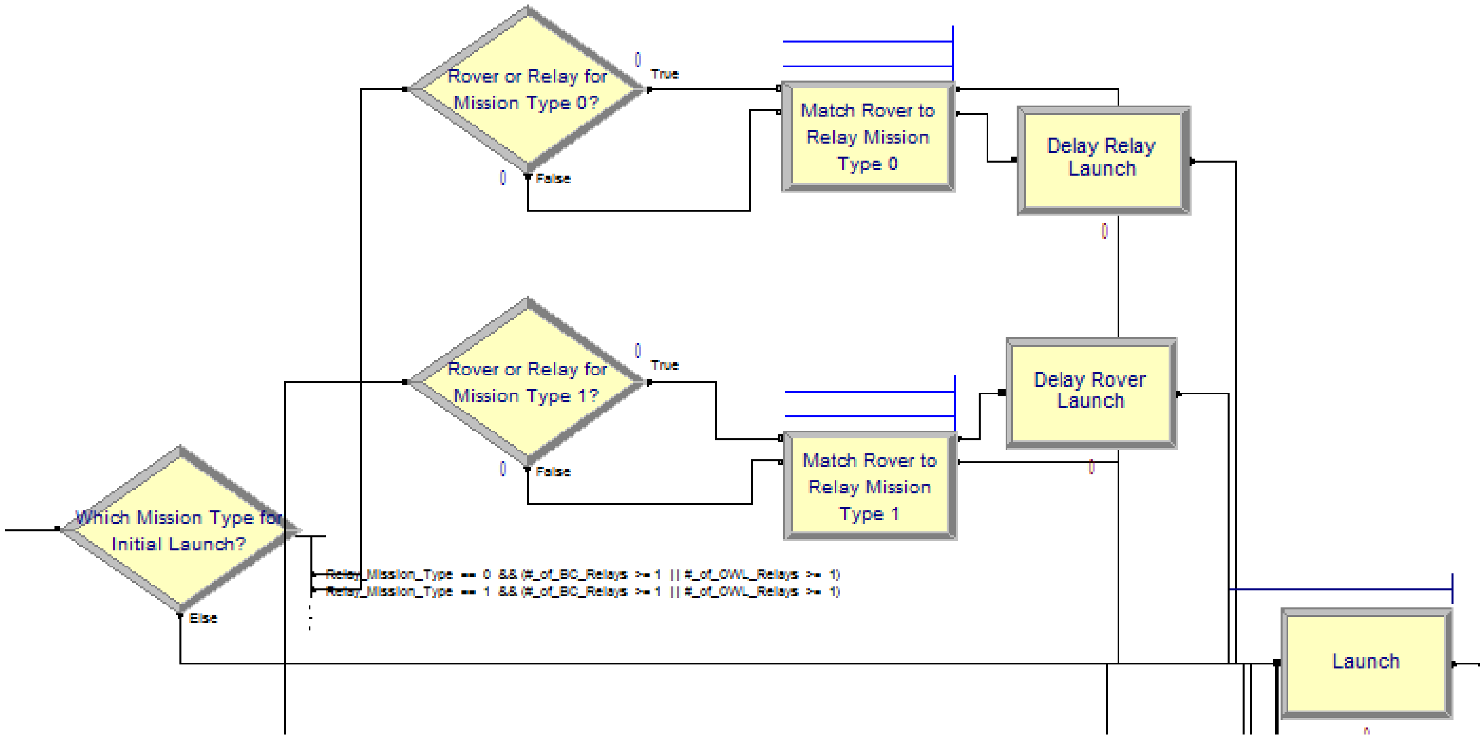

Figure 18: Launch Process for Rover with No Relays

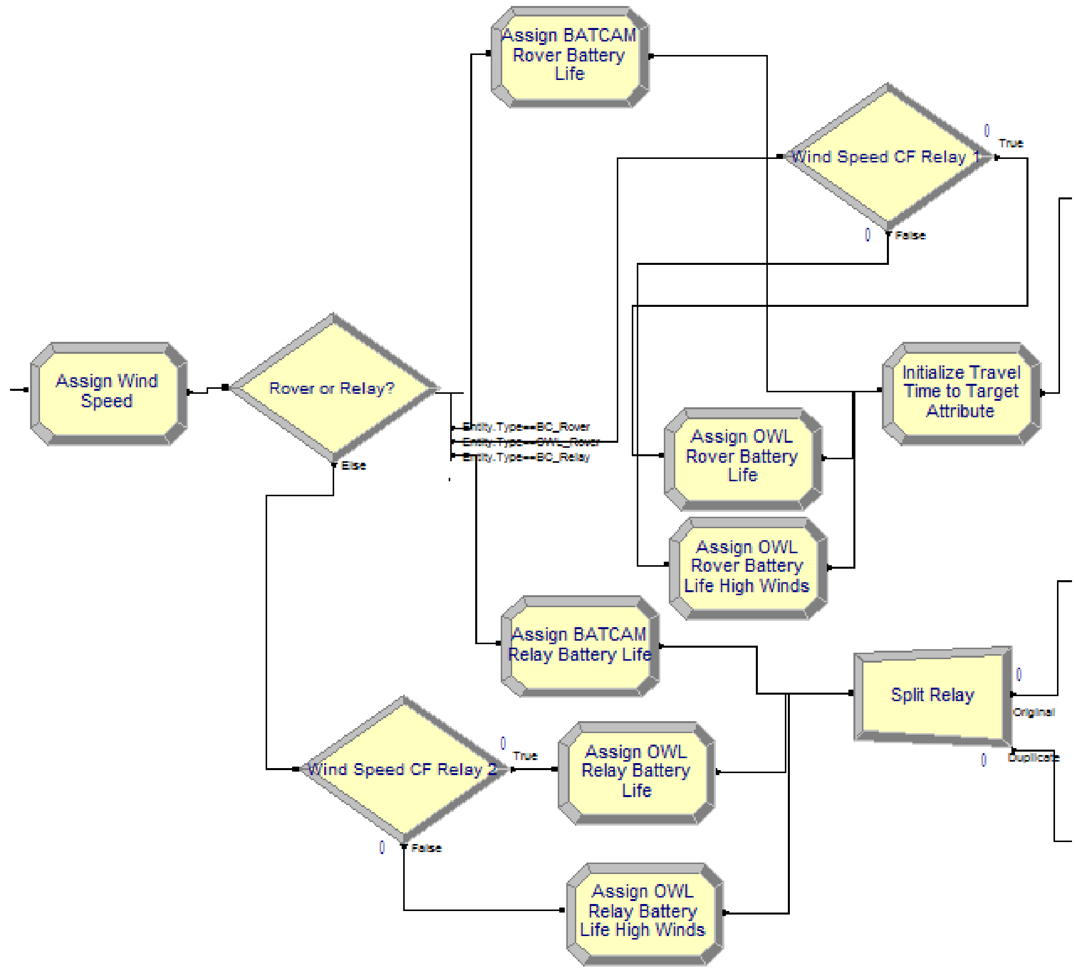

Figure 19: Assignment of Wind Speed Variable, Wind Speed Correction Factor, and Battery Endurance

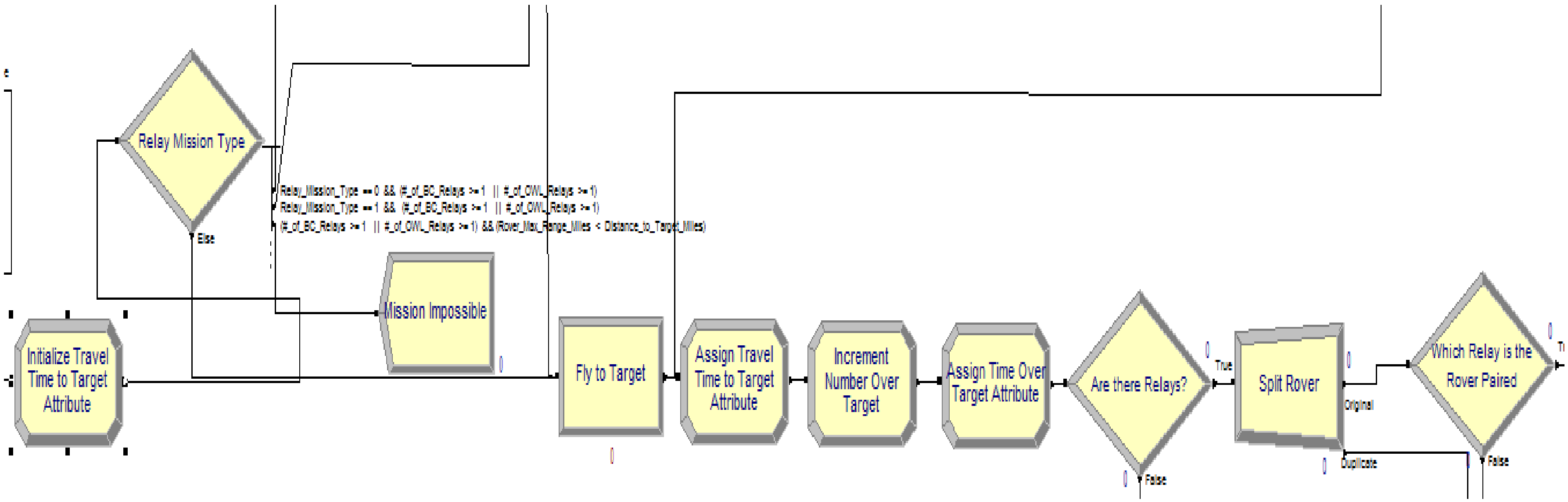

Figure 20: Rover travel to target processes

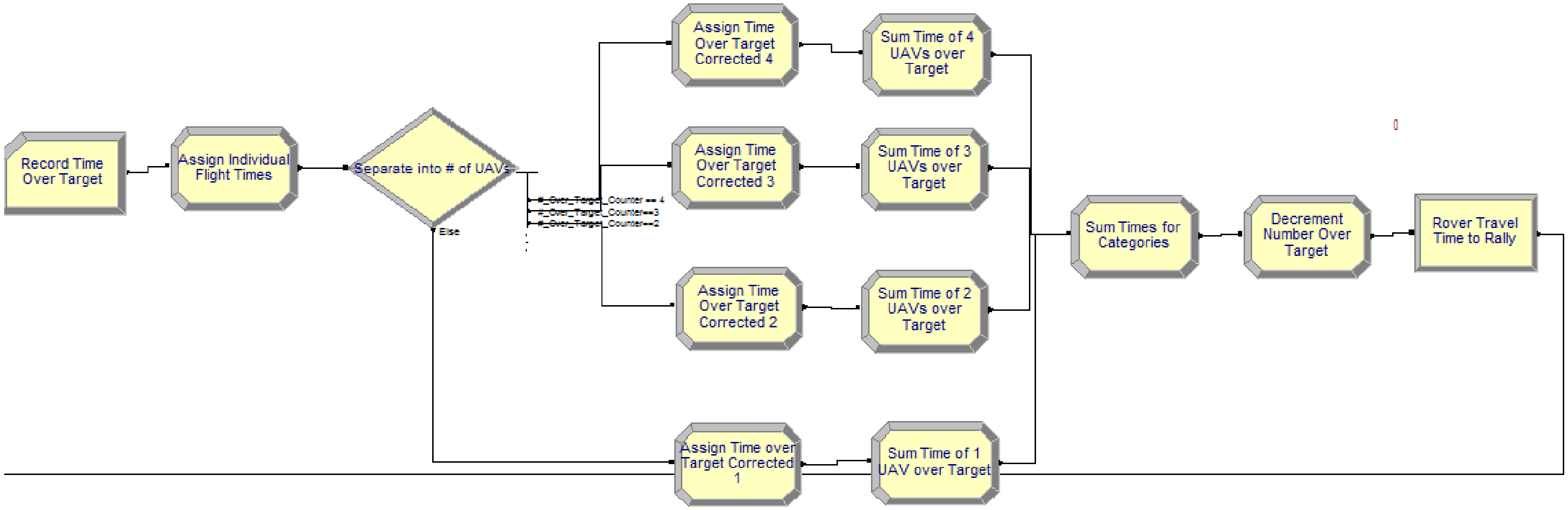

Figure 21: Time Over Target Correction Factor and Rover Travel Time to Rally

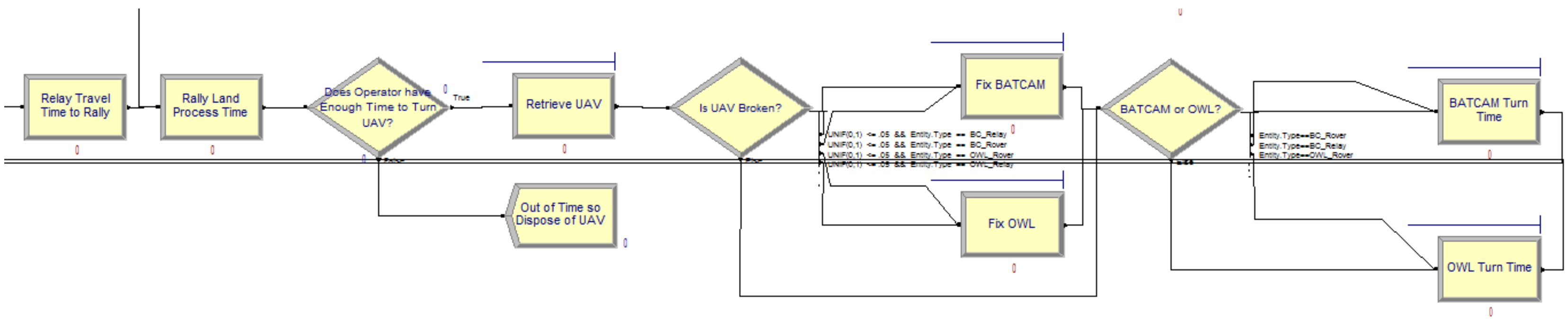

Figure 22: Repair and Maintenance

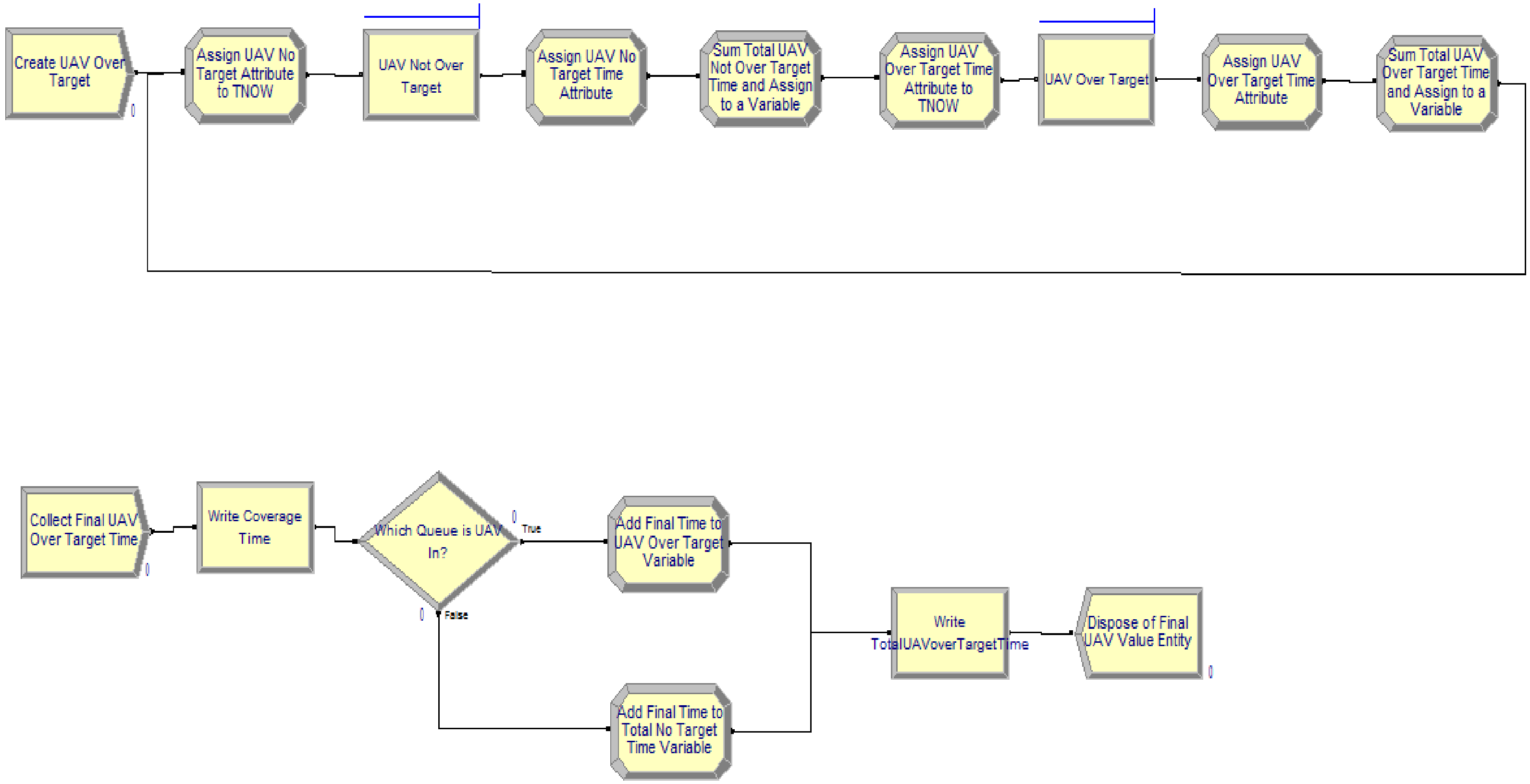

Figure 23: Time Over Target Sub-Model

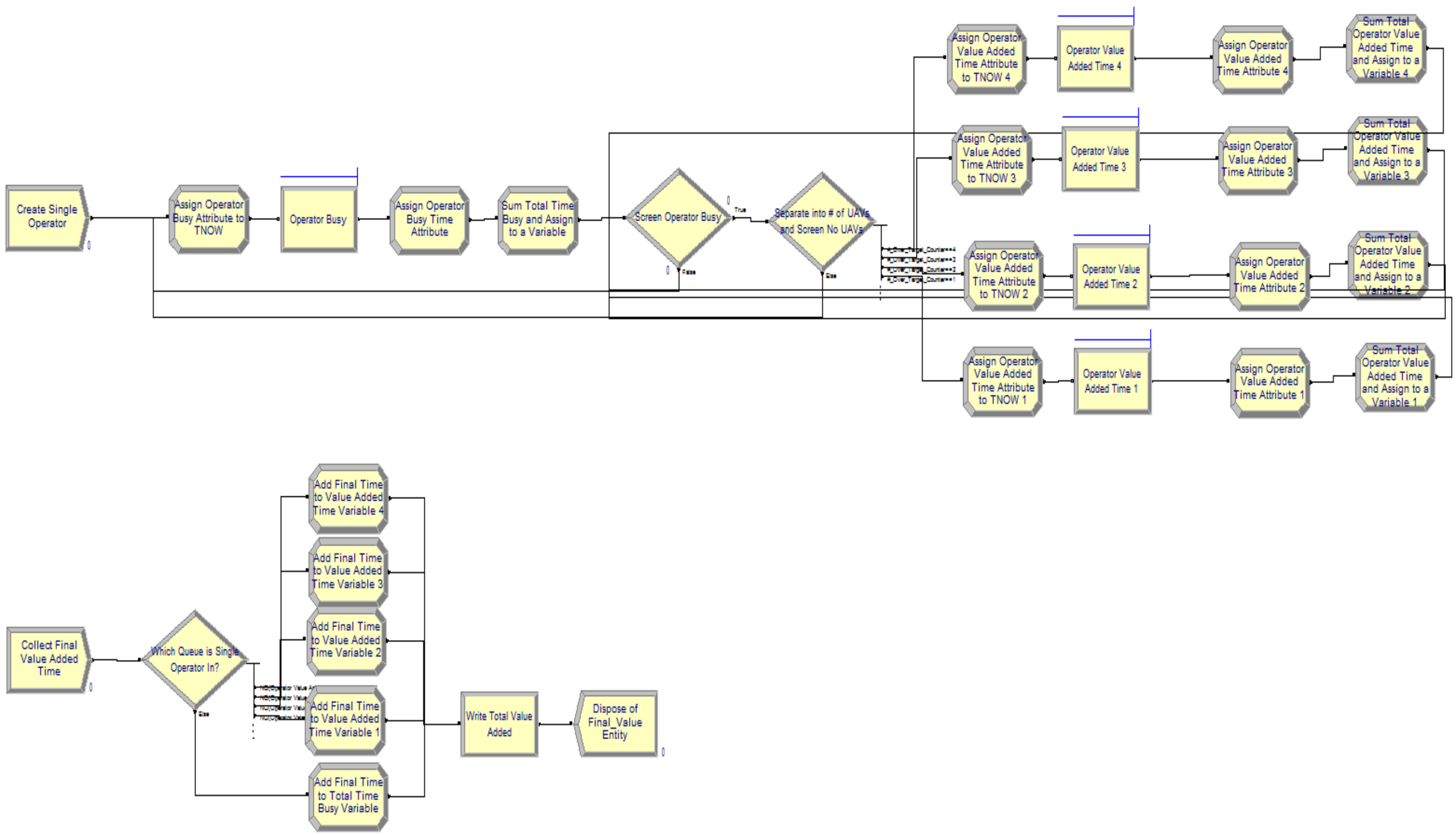

Figure 24: Value Added Time Sub-Model

Appendix B: UAV Team Flight Test Procedures

(Operational Tests are tests 9 and 10 – highlighted)

Flight Test #1 (24-25 September 2012)

1. Preflight testing (completed at AFIT and in field)
    a. Communication check (initial)
    b. Control Surface check
    c. Trim Radio and save settings
    d. Communication check (distance)
2. In Flight Testing With Mission Planner
    a. OWL_A1 & OWL_A2
        i. Zero Sensors
        ii. Set Fail Safe Parameters
        iii. Trim Radio
        iv. Load Waypoints
        v. Launch OWL_A*
        vi. RC Pilot Flight
            1. Adjust Trim
        vii. Engage Autopilot
            1. Adjust Gains (as necessary)
        viii. RC Pilot Landing
        ix. Group Discussion Observations
    b. Sig Rascal_P1 (Petrol) & Sig Rascal_E1 (Electric)
        i. Zero Sensors
        ii. Set Fail Safe Parameters
        iii. Trim Radio
        iv. Load Waypoints
        v. Launch Rascal_*
        vi. RC Pilot Flight
            1. Adjust Trim
        vii. Engage Autopilot
            1. Adjust Gains (as necessary)
        viii. RC Pilot Landing
        ix. Group Discussion Observations
3. In Flight Testing With QGroundControl
    a. Communication check (initial)
    b. Control Surface check
    c. OWL_A1 Flight
        i. Zero Sensors
        ii. Set Fail Safe Parameters
        iii. Trim Radio

        iv. Load Waypoints
        v. Launch OWL_A1
        vi. RC Pilot Flight To Elevation
        vii. Engage Autopilot (observe QGroundControl)
            1. Try update of race track in flight
            2. Observe data logging capabilities
        viii. Land OWL_A1
        ix. Group Discussion Observations
    d. OWL_A2 Flight
        i. Zero Sensors
        ii. Set Fail Safe Parameters
        iii. Trim Radio
        iv. Load Waypoints
        v. Launch OWL_A2
        vi. RC Pilot Flight To Elevation
        vii. Engage Autopilot
        viii. Land OWL_A2
4. Multi-Aircraft Simultaneous Flight 1 With QGroundControl
    a. Replace batteries in OWL_A1 & OWL_A2
    b. Zero Sensors in OWL_A1 & OWL_A2
    c. Set Fail Safe Parameters in OWL_A1 & OWL_A2
    d. Load Waypoints for OWL_A1(elevation 350ft) & OWL_A2 (elevation 200ft)
    e. Launch OWL_A1
    f. RC Pilot Flight To Elevation
    g. Engage Autopilot Observe Lap
    h. Launch OWL_A2
    i. RC Pilot Flight To Elevation
    j. Engage Autopilot Observe Lap
    k. Update Waypoints OWL_A1
    l. Update Waypoints OWL_A2
    m. Land OWL_A1
    n. Land OWL_A2
    o. Group Discussion Observations
5. Multi-Aircraft Simultaneous Flight 1 With QGroundControl
    a. Replace batteries in OWL_A1 & Refill Petrol in Sig Rascal_P1
    b. Zero Sensors in OWL_A1 & Sig Rascal_P1
    c. Set Fail Safe Parameters in OWL_A1 & Sig Rascal_P1
    d. Load Waypoints for OWL_A1(elevation 250ft) & Sig Rascal_P1 (elevation 400ft)
    e. Launch Sig Rascal_P1
    f. RC Pilot Flight To Elevation
    g. Engage Autopilot Observe Lap
    h. Launch OWL_A1
    i. RC Pilot Flight To Elevation

j. Engage Autopilot Observe Lap
k. Update Waypoints Sig Rascal_P1
l. Update Waypoints OWL_A1
m. Land OWL_A1
n. Land Sig Rascal_P1
o. Group Discussion Observations

Flight Test #2 (5-7 November 2012)

1. Initial communications check out
    a. Video feed check (5.4 GHz)
        i. Initial Operation
            1. Is Video feed working?
    b. RC Safety Pilot check (2.4 GHz)
        i. Initial Operation
            1. Is RC Communications working?
        ii. Distance check
            1. On the ground place the FrSky transmitter in range check mode and walk the MAV down the flight line until communications are lost. Do conversion for approximated RC range. Record here _________________
    c. Auto Pilot check (914 MHz)
        i. Initial Operation
            1. Is RC Communications working?
        ii. Distance check
            1. Walk the MAV down the flight line until communications are lost. Record distance here _________________
    d. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance
2. Verify MAVs are flying properly (In Flight Testing With Mission Planner)
    a. Power on RC controllers for OWL_A1 and OWL_A2
    b. For Each OWL_A1, OWL_A2 and Sig_AP
        i. Open Mission Planner
        ii. **Connec**t to MAV at baud rate of 57600
        iii. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
        iv. Verify that the altitude read out on the right of the flight data screen reads **0**
        v. **Repeat** iii-iv as necessary until successful
        vi. Trim Radio

vii. Load Waypoints
viii. Launch MAV
ix. RC Pilot Flight
1. Adjust Trim
x. Engage Autopilot
1. Adjust Gains (as necessary) **SEE APPENDIX**
xi. RC Pilot Landing
c. Group Discussion Observations
d. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance
3. Single MAV flight using QGroundControl (First test OWL_A2 , repeat procedure for Sig_AP)
a. Power on RC controllers OWL_A2 and Sig_AP
b. Zero Sensors
i. Open Mission Planner
ii. **Connec**t to MAV at baud rate of 57600
iii. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
iv. Verify that the altitude read out on the right of the flight data screen reads **0**
v. **Repeat** as necessary until successful
vi. **Close Mission Planner but do NOT power off MAV**
c. Trim Radio
d. **Open UNMODIFIED qgroundcontrol**
e. **Connect** to MAV at baud rate of 57600
f. **Wait for GPS to find location**
g. **Load Waypoints** using waypoint widget
h. **Verify Waypoints** by going to the onboard tab of the waypoint widget and clicking refresh
i. Launch
j. RC Pilot Flight To Elevation
k. Engage Autopilot
i. Try update of race track in flight
ii. Observe data logging capabilities
l. Land
m. Group Discussion Observations
n. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance
4. Single MAV Distance Flight to Loss of Communications
a. Power on RC controllers for OWL_A2
b. Zero Sensors
i. Open Mission Planner
ii. **Connec**t to OWL_A2 at baud rate of 57600

        iii. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
        iv. Verify that the altitude read out on the right of the flight data screen reads **0**
        v. **Repeat** as necessary until successful
    c. Trim Radio
    d. **Wait for GPS to find location**
    e. **Load Waypoints** using waypoint widget
    f. **Verify Waypoints** by going to the onboard tab of the waypoint widget and clicking refresh
    g. Send Safety pilot and Observers to remote location (Must have range radio)
        i. Observer will have map of flight pattern
    h. **Verify both teams are ready and we are clear for launch**
    i. Launch
    j. RC Pilot Flight To Elevation
    k. RC Pilot flies OWL_A2 toward primary ground station
    l. Ground control operator is continually attempting to connect
    m. Monitor telemetry to observe when 914 MHz communications are established
    n. Ground control operator notes distance on map where communications were established
    o. Observe if after 30 seconds of flight OWL_A2 beings to navigate toward RTL
    p. Operator then notifies RC pilot to land OWL_A2
    q. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance
5. Multi-MAV Multi-Ground Station Familiarity Test (Direct LOS) Non-autonomous Relay Navigation
    a. Power on RC controllers for OWL_A1 and OWL_A2
    b. On two separate Laptops connect two Digi modems (one to each laptop)
    c. Open X-CTU and verify that each computer is talking to the attached modem successfully
        i. Select the test/query button. The computer is successfully connected if the type and model information is not garbled text
    d. On laptop one (L1) open Mission Planner
        i. **Power on** OWL_A1 while **holding the MAV level and steady**
        ii. **Connec**t to OWL_A1 at baud rate of 57600
        iii. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
        iv. Verify that the altitude read out on the right of the flight data screen reads **0**
        v. **Repeat** iii-iv as necessary until successful

vi. Trim Radio
vii. Load Waypoints

e. On laptop two (L2) open Mission Planner
    i. Zero Sensors
        1. **Open Mission Planner**
        2. **Connec**t to OWL_A2 at baud rate of 57600
        3. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
        4. Verify that the altitude read out on the right of the flight data screen reads **0**
        5. **Repeat** as necessary until successful
        6. **Close Mission Planner but do NOT power off MAV**
    ii. Trim Radio
    iii. **Open UNMODIFIED qgroundcontrol**
    iv. **Connect** to MAV at baud rate of 57600
    v. **Wait for GPS to find location**
    vi. **Load Waypoints** using waypoint widget
    vii. **Verify Waypoints** by going to the onboard tab of the waypoint widget and clicking refresh
f. Launch OWL_A1
    i. RC Pilot Flight To Elevation
    ii. Engage Autopilot
    iii. Verify Operation Status (if oddities are observed, land and trouble shoot) else
g. Launch OWL_A2
    i. RC Pilot Flight To Elevation
    ii. Engage Autopilot
    iii. Verify Operation Status (if oddities are observed, land and trouble shoot) else
h. Maximize flight time of OWL_A1 to 15 minutes of flight without exceeding time limit
i. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance

6. Multi-MAV Multi-Ground Station Familiarity Test (Direct LOS) Autonomous Relay Navigation
    a. Power on RC controllers for OWL_A1 and OWL_A2
    b. On two separate Laptops connect two Digi modems (one to each laptop)
    c. Open X-CTU and verify that the computer is talking to the modem successfully
        i. Select the test/query button. The computer is successfully connected if the type and model information is not garbled text
    d. On laptop one (L1) open Mission Planner

i. **Power on** OWL_A1 while **holding the MAV level and steady**
ii. **Connec**t to OWL_A1 at baud rate of 57600
iii. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
iv. Verify that the altitude read out on the right of the flight data screen reads **0**
v. **Repeat** iii-iv as necessary until successful
vi. Trim Radio
vii. Load Waypoints at altitude of 550 ft

e. On laptop two (L2) open Mission Planner
    i. Zero Sensors
        1. **Open Mission Planner**
        2. **Connec**t to OWL_A2 at baud rate of 57600
        3. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
        4. Verify that the altitude read out on the right of the flight data screen reads **0**
        5. **Repeat** as necessary until successful
        6. **Close Mission Planner but do NOT power off OWL_A2**
    ii. Trim Radio
    iii. **Open MODIFIED qgroundcontrol**
    iv. **Connect** to both MAVs at baud rate of 57600 (do not enable multiplexing)
    v. **Wait for GPS to find location**
    vi. **Click** on map as close as possible to the location of the ground station as possible
f. Launch OWL_A1
    i. RC Pilot Flight To Elevation
    ii. Engage Autopilot
    iii. Verify Operation Status (if oddities are observed, land and trouble shoot) else
g. Launch OWL_A2
    i. RC Pilot Flight To Elevation
    ii. Engage Autopilot
    iii. Every 5 seconds click anywhere on the map
    iv. Verify Operation Status (if oddities are observed, land and trouble shoot) else
h. Maximize flight time of first MAV to 15 minutes of flight without exceeding time limit
    i. Take manual control of MAV OWL_A2 and land it
    ii. Take manual control of MAV OWL_A1 and land it

- i. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance

7. Multi-MAV Multi-Ground Station Familiarity Test (Direct LOS) Autonomous Relay Navigation **with SIG_AP in place of OWL_A2**
    a. Power on RC controllers for OWL_A1 and OWL_A2
    b. Switch Sig_AP Aircraft ON (leave Autopilot switch OFF)
    c. **Power on** OWL_A1 while **holding the MAV level and steady**
    d. On laptop one (L1) open Mission Planner
        i. Plug in Ch1-Relay modem to laptop L1
        ii. **Connec**t to OWL_A1 at baud rate of 57600
        iii. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
        iv. Verify that the altitude read out on the right of the flight data screen reads **0**
        v. **Repeat** iii-iv as necessary until successful
        vi. Trim Radio
        vii. Load Waypoints
    e. Switch Sig_AP Autopilot ON
    f. On laptop two (L2) open Mission Planner
        i. Plug in Ch1-Sig modem to laptop L2
        ii. Zero Sensors
            1. **Open Mission Planner**
            2. **Connec**t to Sig_AP at baud rate of 57600
            3. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
            4. Verify that the altitude read out on the right of the flight data screen reads **0**
            5. **Repeat** as necessary until successful
            6. Hold Sig_AP level
            7. Under the configuration tab click on the calibrate level
            8. Verify on the flight data tab that the hud is showing level flight
            9. **Close Mission Planner but do NOT power off MAV**
        iii. Trim Radio
        iv. **Open MODIFIED qgroundcontrol**
        v. **Connect** to Sig_AP at baud rate of 57600
        vi. **Wait for GPS to find location**
        vii. **Select** MAV001 (Sig) for control
        viii. **Load Waypoints** using waypoint widget
        ix. **Verify Waypoints** by going to the onboard tab of the waypoint widget and clicking refresh
    g. Launch OWL_A1
        i. RC Pilot Flight To Elevation
        ii. Engage Autopilot

iii. Verify Operation Status (if oddities are observed, land and trouble shoot) else

h. Launch Sig_AP
    i. RC Pilot Flight To Elevation
    ii. Engage Autopilot
    iii. Verify Operation Status (if oddities are observed, land and trouble shoot) else

i. Maximize flight time of OWL_A1 to 15 minutes of flight without exceeding time limit
    i. Take manual control of MAV Sig_AP and land it
    ii. Take manual control of MAV OWL_A1 and land it

j. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance

8. Beyond Communications Line Of Sight (BCLOS) Flight Test
    a. Power on RC controllers for OWL_A1 and OWL_A2
    b. Switch Sig_AP Aircraft ON (leave Autopilot switch OFF)
    c. **Power on** OWL_A1 while **holding the MAV level and steady**
    d. On laptop one (L1) open Mission Planner
        i. Plug in Ch1-Relay modem to laptop L1
        ii. **Connec**t to OWL_A1 at baud rate of 57600
        iii. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
        iv. Verify that the altitude read out on the right of the flight data screen reads **0**
        v. **Repeat** iii-iv as necessary until successful
        vi. Trim Radio
        vii. Load Waypoints
    e. Switch Sig_AP Autopilot ON
    f. On laptop two (L2) open Mission Planner
        i. Plug in Ch1-Sig modem to laptop L2
        ii. Zero Sensors
            1. Open Mission Planner
            2. **Connec**t to Sig_AP at baud rate of 57600
            3. On the **Flight Data** tab select the **Actions** tab and click **Set Home Alt**
            4. Verify that the altitude read out on the right of the flight data screen reads **0**
            5. **Repeat** as necessary until successful
            6. Hold Sig_AP level
            7. Under the configuration tab click on the calibrate level
            8. Verify on the flight data tab that the hud is showing level flight

9. **Close Mission Planner but do NOT power off MAV**
    i. Trim Radio
    ii. **Open MODIFIED qgroundcontrol**
    iii. **Connect** to Sig_AP at baud rate of 57600
    iv. **Wait for GPS to find location**
    v. **Select** MAV001 (Sig) for control
    vi. **Load Waypoints** using waypoint widget
    vii. **Verify Waypoints** by going to the onboard tab of the waypoint widget and clicking refresh
    b. Send out RC pilot and distant area observer with map of flight path, cell phone and range radio
    c. Launch SIG_AP
        i. RC Pilot Flight To Elevation and approximate relay position
    d. Launch OWL_A1
        i. RC Pilot Flight To Elevation
        ii. Engage Autopilot
        iii. Verify Operation Status (if oddities are observed, land and trouble shoot) else
    e. Ground Control Operator verifies that relay of communications is operational
        i. Is telemetry data displaying in the ground control software?
        ii. Can information be written to the rover MAV?
        iii. If yes proceed. If no fly OWL_A1 closer to Sig_AP.
    f. **On Sig_AP**
        i. Engage Autopilot
        ii. Every 5 seconds click anywhere on the map
        iii. Verify Operation Status (if oddities are observed, land and trouble shoot)
    g. Maximize flight time of OWL_A1 to 15 minutes of flight without exceeding time limit
    h. On ground control operator's que both RC pilots take control of their respective MAVs and land the MAVs
    i. Record and Measure time spent fixing, recovering, launching, turning, flight time, wind speed, battery endurance
10. Stationary Target Flight Test
    a. Emplace stationary target
    b. Set waypoint pattern to loiter over target
    c. Launch OWL and monitor to ensure proper flight path
    d. Record and Measure loiter time and target observed time
11. Road Surveillance Flight Test
    a. Designate linear zone of observation

b. Set waypoint pattern to observe linear zone of observation
c. Launch OWL and monitor to ensure proper flight path
d. Record and Measure loiter time and target observed time

Appendix C: Field of View Algorithm – Loiter Pattern

```
%
%  Plots for J. Welborn thesis, March 2013
%

% data set for Loiter, counterclockwise
adjdata=xlsread('Welborn Telemetry Log_7Nov12.xlsx','Adjusted Data');

% time/date not used
timedata=adjdata(:,1:3);

%extract 6 columns: yaw, pitch, roll, long lat, elev
data=adjdata(:,[6 4 2 12 16 18]);
clear adjdata;

%change North (0 yaw) to positive x axis
data2 = [ data(:,1)-90 data(:,2:6)];
clear data

figure
plot(0,0,'r*');hold on;
plot(data2(1:5:14000,4),data2(1:5:14000,5))
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
legend('homebase', 'UAV location')
title('Aircraft Location - Full 7NovAdjusted data')
axis([-400 0 0 300])
grid


figure
plot(0,0,'r*');hold on;
plot(data2(1:5:600,4),data2(1:5:600,5))
s=[];
for i = 1:5: 600
t=sensoraimpoint2(data2(i,4:6),[-data2(i,1) data2(i,2) -
data2(i,3)],'l');
s=[s; t];
end
plot(s(:,1), s(:,2),'g')
legend('homebase', 'UAV location', 'aimpoint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor aimpoint -  7NovAdjusted  data')
axis([-400 0 0 300])
grid

figure
startt=1;
stept=50;
```

```
endt=600;
s=[];
for i = 1:600
t=sensoraimpoint2([data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'l');
s=[s; t];
end
plot(0,0,'r*');
hold on;
plot(data2(startt:stept:endt,4),data2(startt:stept:endt,5))
plot(s(startt:stept:endt,1), s(startt:stept:endt,2),'g')
for i=startt:stept:endt
    f=footprint3([data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'l');
    plot(f(:,1), f(:,2),'r')
end
legend('homebase', 'UAV location', 'aimpoint','footprint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor Footprint 7NovAdjusted  data')
axis([-400 0 0 300])
grid

%calculate %view of target
%assume target is located at -240, 140 is loiter point
cnt=0;
endt=14000;
for i = 1:endt
    f=footprint3([data2(i,4:6)],[-data2(i,1) data2(i,2) -
data2(i,3)],'l');
    cnt=cnt+inpolygon(-240, 140,f(:,1),f(:,2));
end
fprintf('The %2.2f percent of telemetry points have a sensor footprint
that covers the loiter point (-240, 140)\n', 100*cnt/endt);

%
%
clear all
%
%
% data set for Loiter, clockwise
adjdata=xlsread('Welborn Telemetry Log_7Nov12 #2.xlsx','Adjusted Data
Loiter');
data=adjdata(:,[6 4 2 12 16 18]);
clear adjdata;

data2= [ data(:,1)-90, data(:,2:6)];
clear data

figure
plot(0,0,'r*');hold on;
plot(data2(1:5:7000,4),data2(1:5:7000,5))
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
```

```
legend('homebase', 'UAV location')
title('Aircraft Location - Full Log_7Nov12 #2 Adjusted data')
axis([-250 50 -100 200])
grid

figure
plot(0,0,'r*');hold on;
plot(data2(1:5:800,4),data2(1:5:800,5))
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
legend('homebase', 'UAV location')
title('Aircraft Location - First rotation Log_7Nov12 #2 Adjusted data')
axis([-250 50 -100 200])
grid

figure
plot(0,0,'r*');hold on;
plot(data2(1:5:7000,4),data2(1:5:7000,5))
s=[];
for i = 1:5: 7000
t=sensoraimpoint2(data2(i,4:6),[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
plot(s(:,1), s(:,2),'g')
legend('homebase', 'UAV location', 'aimpoint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor aimpoint -  Full Log_7Nov12 #2 Adjusted data')
grid
axis([-250 50 -100 200])


figure
plot(0,0,'r*');hold on;
plot(data2(1:5:800,4),data2(1:5:800,5))
s=[];
for i = 1:5: 800
t=sensoraimpoint2(data2(i,4:6),[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
plot(s(:,1), s(:,2),'g')
legend('homebase', 'UAV location', 'Sensor aimpoint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor aimpoint Resonance -  Full Log_7Nov12 #2 Adjusted data')
grid
axis([-250 50 -100 200])

% this block focuses on a natural resonance in the aimpoint (wind?)
figure
plot(0,0,'r*');hold on;
plot(data2(1:1:800,4),data2(1:1:800,5))
```

```
s=[];
for i = 400:1: 600
t=sensoraimpoint2(data2(i,4:6),[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
plot(s(:,1), s(:,2),'g')
legend('homebase', 'UAV location', 'Sensor aimpoint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor aimpoint Resonance -  Full 7Nov12 #2 Adjusted data')
grid
plot(data2(400:1:600,4),data2(400:1:600,5),'k*')
axis([-250 50 -100 200])

%actual altitude
figure
startt=1;
stept=50;
endt=800;
s=[];
for i = 1:800
t=sensoraimpoint2([data2(i,4:6)],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
plot(0,0,'r*');
hold on;
plot(data2(startt:5:endt,4),data2(startt:5:endt,5))
plot(s(startt:5:endt,1), s(startt:5:endt,2),'g')
for i=startt:stept:endt
    f=footprint3([data2(i,4:6)],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
    plot(f(:,1), f(:,2),'r')
end
legend('homebase', 'UAV location', 'aimpoint','footprint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor Footprint 7NovAdjusted #2 data')
axis([-250 50 -100 200])
grid

%what if altitude was only 100m
figure
startt=1;
stept=50;
endt=800;
s=[];
for i = 1:800
t=sensoraimpoint2([data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
plot(0,0,'r*');
```

```
hold on;
plot(data2(startt:5:endt,4),data2(startt:5:endt,5))
plot(s(startt:5:endt,1), s(startt:5:endt,2),'g')
for i=startt:stept:endt
    f=footprint3([data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
    plot(f(:,1), f(:,2),'r')
end
legend('homebase', 'UAV location', 'aimpoint','footprint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor Footprint 7NovAdjusted #2 data (100m altitude)')
axis([-250 50 -100 200])
grid

%calculate %view of target using actual altitude
%assume target is located at -100 50 is loiter point
cnt=0;
endt=7000;
for i = 1:7000
    f=footprint3([data2(i,4:6)],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
    cnt=cnt+inpolygon(-100, 50,f(:,1),f(:,2));
    end

fprintf('The %2.2f percent of telemetry points have a sensor footprint
that covers the loiter point (-100 50)at actual altitude\n',
100*cnt/7000);
%calculate %view of target at 100m altitude
%assume target is located at -100 50 is loiter point
cnt=0;
endt=7000;
for i = 1:7000
    f=footprint3([data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
    cnt=cnt+inpolygon(-100, 50,f(:,1),f(:,2));
    end

fprintf('The %2.2f percent of telemetry points have a sensor footprint
that covers the loiter point (-100 50) at 100m altitude\n',
100*cnt/7000);

%
%
clear all
%
%
% data set for Hex Pattern (road runway surveillance), clockwise
adjdata=xlsread('Welborn Telemetry Log_7Nov12 #2.xlsx','Adjusted Data
Hex');
data=adjdata(:,[6 4 2 12 16 18]);
clear adjdata;
data2= [ data(:,1)-90, data(:,2:6)];
clear data
```

```
figure
plot(0,0,'r*');hold on;
plot(data2(1:5:13000,4),data2(1:5:13000,5))
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
legend('homebase', 'UAV location')
title('Aircraft Location - Full 7NovAdjusted Hex data')
axis([-200 100 -300 300])
grid


figure
plot(0,0,'r*');hold on;
plot(data2(1000:5:13000,4),data2(1000:5:13000,5))
s=[];
for i = 1000:5: 13000
t=sensoraimpoint2( [data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
plot(s(:,1), s(:,2),'g')
legend('homebase', 'UAV location', 'aimpoint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor aimpoint -  7NovAdjusted Hex data')
grid
axis([-200 100 -300 300])


%what if altitude was 100m
figure
startt=2500;
stept=25;
endt=2800;
s=[];
for i = 1:3000
t=sensoraimpoint2([data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
figure
plot(0,0,'r*');
hold on; grid on;
plot(data2(1000:5:3000,4),data2(1000:5:3000,5))
plot(s(startt:5:endt,1), s(startt:5:endt,2),'g')
for i=startt:stept:endt
    f=footprint3([data2(i,4:5) 100],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
    plot(f(:,1), f(:,2),'r')
end
road=[-90 185; -30 -175];
plot(road(:,1),road(:,2),'k')
plot(data2(startt:stept:endt,4),data2(startt:stept:endt,5),'k*')
```

```
legend('homebase', 'UAV location', 'aimpoint','footprint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor Footprint 7NovAdjusted Hex data (100m altitude)')
axis([-200 100 -300 300])

%actual altitude
figure
startt=2500;
stept=25;
endt=2800;
s=[];
for i = 1:3000
t=sensoraimpoint2([data2(i,4:6)],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
s=[s; t];
end
figure
plot(0,0,'r*');
hold on; grid on;
plot(data2(1000:5:3000,4),data2(1000:5:3000,5))
plot(s(startt:5:endt,1), s(startt:5:endt,2),'g')
for i=startt:stept:endt
    f=footprint3([data2(i,4:6)],[-data2(i,1) data2(i,2) -
data2(i,3)],'r');
    plot(f(:,1), f(:,2),'r')
end
road=[-90 185; -30 -175];
plot(road(:,1),road(:,2),'k')
plot(data2(startt:stept:endt,4),data2(startt:stept:endt,5),'k*')
legend('homebase', 'UAV location', 'aimpoint','footprint')
xlabel('Long distance from homebase (m)')
ylabel('Lat distance from homebase (m)')
title('Sensor Footprint 7NovAdjusted Hex data (actual altitude)')
axis([-200 100 -300 300])
```

Appendix D: Field of View Algorithm – Sensor Aimpoint

```
function sensor_aimpoint = sensoraimpoint2(acft_pos,acft_att,camera)
% sensor_aimpoint = sensoraimpoint(acft_pos,acft_att,sens_att)
% Determines the position on the ground where the sensor is currently
%   aimed, based on aircraft position, aircraft attitude, and sensor
%   attitude.  Assumes a North-East-Down system.
%
% INPUTS:
%   acft_pos : a 1x3 vector of the aircraft's current postion in m
%               (x, y, z).  Assumes z is same as AGL altitude.
%   acft_att : a 1x3 vector of the aircraft attitude angles in degrees
%               (yaw, pitch, roll)
%   camera : 'c', 'l','r' center left or right camera on RAVEN RQ-11B
%
% OUTPUTS:
%   sensor_aimpoint : a 1x3 vector of the sensor aimpoint, assuming z =
0
%       if the aircraft (x,y) position is given as (0,0), the sensor
%           aimpoint is relative to the aircraft position, not to the
earth
%
% NOTES:
%   x-axis - positive out the nose
%   y-axis - positive out the RIGHT wing
%   z-axis - positive TOWARDS the GROUND
%   Yaw    - positive as nose goes to the right from pilot's
perspective
%               0 out the nose; +90deg out right wing; -90deg out left
wing
%   Pitch  - positive nose up
%   Roll   - positive as left wing rises
%
%   Sensor Roll should always be 0.  It just changes with Azmith (Yaw)
and
%       Elevation (Pitch).

if nargin==0
    % Edit these to change the default test case
    acft_pos = [00,00,100];
    acft_att = [deg2rad(0) deg2rad(0) deg2rad(0)];
    %sens_att = [deg2rad(00) deg2rad(-49) deg2rad(00)]; % Front Sensor
    sens_att = [deg2rad(-90) deg2rad(-39) deg2rad(00)]; % Side Left
Sensor
    %  sens_att = [deg2rad(90) deg2rad(-39) deg2rad(00)]; % Side
"right" Sensor
end
if nargin == 2
        acft_att=  deg2rad(acft_att);
        sens_att = [deg2rad(-90) deg2rad(-39) deg2rad(00)]; % Side left
Sensor assumed
end
if nargin == 3
        acft_att=  deg2rad(acft_att);
```

```
        if camera == 'c'
             sens_att = [deg2rad(00) deg2rad(-49) deg2rad(00)]; % Front
Sensor
        elseif camera == 'l'
             sens_att = [deg2rad(-90) deg2rad(-39) deg2rad(00)]; % Side
Left Sensor
        else %'r'
            sens_att = [deg2rad(90) deg2rad(-39) deg2rad(00)]; % Side
"right" Sensor
        end
end

% Create a sensor unit vector that points out the nose of the aircraft.
% This can then be rotated to find the unit vector where the sensor is
% aimed.
sens_vec = [1 0 0]';

% angle2dcm is a MATLAB command that does the direction cosine matrix
from
%   rotation angles.  It finds reference to body direction cosine
matrix.
%   C = data( yaw, pitch, roll ) where C is direction cosine matrix.
% angle2dcm' finds body to reference frames

% This produces a unit vector that points at the target from the sensor
and
% is in NED coordinate system.
aim_vector =
angle2dcm(acft_att(1),acft_att(2),acft_att(3))'*angle2dcm(sens_att(1),s
ens_att(2),sens_att(3))'*sens_vec;

% Get the angle in the vertical realm from target to sensor unit
vector.
tan_theta = aim_vector(3)/sqrt(aim_vector(1)^2+aim_vector(2)^2);

% Get the horizontal distance across an assumed 2-D flat-plane earth
horizontal_distance = acft_pos(3)/tan_theta;

% Get the angle in the horizontal plane from target to sensor unit
vector.
psi = atan2(aim_vector(2),aim_vector(1));

% Get the (x,y) of the target
 if aim_vector(3)>0 % if z is pointed towards the ground
    x = acft_pos(1)+horizontal_distance*cos(psi);
    y = acft_pos(2)+horizontal_distance*sin(psi);
     z = 0;
    sensor_aimpoint = [x,y,z];
else % if z does not aim towards the ground
    sensor_aimpoint = [NaN,NaN,NaN];
end
```

Appendix E: Field of View Algorithm – Footprint

```
function footprint = footprint3(acft_pos,acft_att,camera)
%footprint = footprint(acft_pos,acft_att,sens_att,fov)
% Generates a sensor footprint for a RAVEN aircraft from
location/attitude
%
% INPUTS:
%   acft_pos        : a 1x3 vector of the aircraft's current postion in
m
%                   (x,y,z).  Assumes z is same as AGL altitude.
%   acft_att        : a 1x3 vector of the aircraft attitude angles in
degrees
%                   (yaw, pitch, roll)
%   camera          : 'c', 'l','r' center left or right camera on RAVEN
RQ-11B

% OUTPUTS:
%   footprint    : a 5x3 vector of the sensor footprint
%                   row 1 = bottom right corner
%                   row 2 = bottom left corner
%                   row 3 = top left corner
%                   row 4 = top right corner
%                   row 5 = bottom right corner

if nargin==0
    acft_pos     = [-173,00,100]; %test case
    acft_att     = [deg2rad(00) deg2rad(00) deg2rad(00)];
    sens_att     = [deg2rad(-90) deg2rad(-39) deg2rad(00)]; % Side left
Sensor
    fov          = [deg2rad(48),deg2rad(40)]; % h_fov and v_fov
end
if nargin==2
    sens_att     = [deg2rad(-90) deg2rad(-39) deg2rad(00)]; % Side left
Sensor
    acft_att     = [deg2rad(acft_att)];
    fov          = [deg2rad(48),deg2rad(40)]; % h_fov and v_fov
end
if nargin==3
     fov          = [deg2rad(48),deg2rad(40)]; % h_fov and v_fov
     acft_att     = deg2rad(acft_att);
     if camera == 'c'
             sens_att = [deg2rad(00) deg2rad(-49) deg2rad(00)]; % Front
Sensor
     elseif camera == 'l'
             sens_att = [deg2rad(-90) deg2rad(-39) deg2rad(00)]; % Side
Left Sensor
     else %'r'
            sens_att = [deg2rad(90) deg2rad(-39) deg2rad(00)]; % Side
"right" Sensor
     end
end
```

```
% Set up the maximum distance allowed for the footprint to reach before
% cutting it off
max_dist = inf; % meters

% Set up the field of view
h_fov = fov(1);v_fov = fov(2);

% Create the sensor footprint for a sensor out the front
footprint = [ 1      +tan(h_fov/2)    +tan(-v_fov/2); % bottom right
corner
              1      -tan(h_fov/2)    +tan(-v_fov/2); % bottom left
corner
              1      -tan(h_fov/2)    +tan(+v_fov/2); % top left corner
              1      +tan(h_fov/2)    +tan(+v_fov/2); % top right corner
              1      +tan(h_fov/2)    +tan(-v_fov/2)];% bottom right
corner

% Rotate the sensor footprint
for jj=1:5
        a= angle2dcm(acft_att(1),acft_att(2),acft_att(3))';
        b=angle2dcm(sens_att(1),sens_att(2),sens_att(3))';
        c=footprint(jj,:)';
        footprint(jj,:) = a*b*c;

    % Parametericize the footprint
    t = acft_pos(3)/footprint(jj,3);
    t = acft_pos(3)/abs(footprint(jj,3));
    z = 0;
    y = acft_pos(2)+t*footprint(jj,2);
    x = acft_pos(1)+t*footprint(jj,1);
    if norm([x y z])>max_dist
        theta = atan2(y,x);
        x = max_dist*cos(theta);
        y = max_dist*sin(theta);
    end
    footprint(jj,:)=[x y z];
end
```

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14. ABSTRACT
This research improved a simulation that models a single operator responsible for multiple UAV rovers. The improvement calibrated the model by increasing the realism of its expected time that the target will be within the field of view of a UAV's camera and how much of that will be observed by an operator that has multiple tasks to perform throughout the mission.The calibration was derived from multiple flight tests, by using a Field of View Algorithm in MATLAB and by visually recording times for loiter loops by hand. It was determined that the target will be within the field of view of a UAV loitering in a circular pattern between 62% and 66% of the overall loiter time. For an 8 hour beyond line of sight mission, the model's optimal results were 145 min of Value Added Time in low wind conditions and 137 min in high wind. For an 8 hour within line of sight mission, the optimal result was 287 min in low wind conditions and 268 min in high wind.

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